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Contract No.
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THE ROLE OF EXTERIOR LIGHTS IN MID-AIR COLLISION PREVENTION

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PROJECT NO. 110-512 R

prepared for

FEDERAL AVIATION AGENCY

Systems Research and Development Service

by

APPLIED PSYCHOLOGY CORPORATION

4113 LEE HIGHWAY

ARLINGTON 7, VIRGINIA

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Contract No. FAA/BRD-127
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THE ROLE OF EXTERIOR LIGHTS IN MID-AIR COLLISION PREVENTION

Prepared for

Federal Aviation Agency
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Washington 25, D. C.

Project No. 110-512R

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Applied Psychology Corporation, Arlington, Virginia
THE ROLE OF EXTERIOR LIGHTS IN MID-AIR COLLISION PREVENTION
Theodore H. Projector, July 1962
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ABSTRACT

This report summarizes that portion of a research program on visual collision-avoidance techniques which deals with the design and use of navigation light systems. The findings are examined from the viewpoint of the Civil Air Regulations, and a three-phase program for improvement is outlined. In Phase I, it is indicated that genuine standardization is urgently needed, and can be achieved with minimum delay with a standard consisting of red, green, and white steady-burning position lights and a red, flashing anti-collision light. In Phase II, an intermediate-range program, the one major defect of the system suggested for Phase I (the absence of left-right indication to the rear) is to be corrected by substitution of a two-color light, yellow and bluish white, for the white taillight. In Phase III, a long-range program, it is suggested that investigation into the possibility of altitude coding in light systems be continued. In all three phases, additional detailed recommendations are made to insure maximum utilization of navigation lights.

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THE ROLE OF EXTERIOR LIGHTS IN

MID-AIR COLLISION PREVENTION

I. INTRODUCTION

The earliest navigation light system used on aircraft was patterned after the system used in marine practice. It consisted of red and green wingtip position lights covering azimuthal sectors from 0° (dead ahead) to 110° abeam, left and right respectively, and a white light covering the remaining sector to the rear. This system remained in use without change until about 1940. At that time, several commercial air lines because of several near collisions in the air and one actual collision on the ground, all involving overtaking courses, requested that the Civil Aeronautics Administration improve conspicuity to the rear. To improve conspicuity and to avoid confusion of the white taillight with other lights, alternately flashing white and red taillights were adopted.

From this time on, one proposal followed another and very soon, a number of navigation light systems, differing more or less from the original system, were in use. Some added other lights to the basic configuration, others changed characteristics of operation.

In the 1950's, a number of proposals which departed more radically from the original configuration were offered. New kinds of light sources were used, different kinds of information were presented, and new ways of codifying information into light signals were tried. In 1955 Special Civil Air Regulation SR 392 was adopted to facilitate experimentation with new systems. Under the regulation, up to 15 installations of a given experimental system might be authorized for a period of six months. Renewals of authorizations have been granted regularly.

At the present time a variety of navigation light systems are installed on aircraft. Some are fairly distinctive, others present signals that are ambiguous--a visual signal in one system presents information that is different from that presented by the same signal in another system. It may be asked whether the diversity of light systems and the ambiguity of some signals add to the danger of collision. Many pilots contend that the information presented by coded signal lights is of no interest to them anyway--they are concerned only with the single item of information that an aircraft is there. Collisions are far fewer at night than in the daytime, and no night collision has been blamed on the inadequacy of light signal information. The analysis of near-miss reports is very difficult and often

speculative, but here again, no clear picture can be obtained of information inadequacy as a source of trouble.

If it is true that no information other than aircraft presence is of value, then it is unreasonable for the CAR to impose a regulation system on aircraft operators. A single light of the highest possible conspicuity is all that should be required, and requirements for sector-coding should be eliminated. Generally speaking, aircraft lights are more visible at night than aircraft themselves in the daytime, and maximum conspicuity would be attained if all available power were concentrated in a single signal visible in all necessary directions. Lighting systems lend themselves to transmitting information, but the need for and usefulness of any given information must be shown before it can reasonably be required on aircraft. If it can be shown that some information is useful enough to be required, then it is essential that (a) the required lighting system present it clearly, and (b) no differing systems be permitted.

This report summarizes the effort of the contractor to investigate the characteristics of navigation light systems and their usefulness in minimizing the risk of collision. In order to do this the various relevant characteristics have been analyzed and isolated. Some of the essential properties of such systems are relatively well understood--the relation between intensity and visibility, for example--and it is only necessary to examine the literature to obtain this information. Other properties, not so well understood, have had to be investigated experimentally. This report deals with the isolated aspects separately, then synthesizes the results. This approach is considered the only effective way to deal with one of the problems that has hitherto made it difficult to make reasonable decisions about lighting systems. As proposed, the systems are usually in the form of completed "hardware" in which many separate characteristics are inextricably combined. It is felt that a rational evaluation of system effectiveness is possible only when each system is analyzed in terms of the separate characteristics--for example, the information presented, the coding technique used to present it, its intensity distribution, its efficiency, weight, size, reliability, etc.

II. THE INFORMATION TRANSMISSIBLE BY NAVIGATION LIGHT SYSTEMS

Any aircraft navigation light, by virtue of being sighted and identified, transmits the most essential information: the presence and location of the aircraft. Every lighting system currently being used provides, in addition, sector information of one kind or another which identifies an azimuthal sector of the sighted aircraft, and consequently, to some degree, its direction of flight. Six additional types of information have been cited as possibly useful if they could be coded into a navigation light system:[1]

1. Identification of aircraft by type or other characteristic;

2. Distance;

3. Altitude;

4. Speed;

5. Attitude (pitch or roll);

6. Maneuver (change of course from straight and/or level).

Of these items of information, which are "essential," which useful, and which of little or no value? If for simplicity it will be necessary to limit the amount of information presented, which items should be included in the system, and how precisely or in how much detail should the information be coded?

Presence, Location, and the Fixity-of-Bearing Criterion

As noted above, the first item, presence and location, is conveyed, without coding, as soon as a light signal is sighted and identified. (Identification as an aircraft light is important; as will be discussed later, aircraft lights are often confused with stars, tower and other obstruction lights, and ground lights.)

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1 A preliminary discussion of information presentation may be found in Projector & Robinson, 1958. A detailed analysis of the usefulness of coded information is contained in Applied Psychology Corporation Technical Report No. 1, January 1961, on which the following discussion is largely based.

No particular coded information is involved in extracting presence and location information from a sighted light. Nevertheless it is possible to use such a signal to determine other useful information about an intruder aircraft, especially one observed for any length of time. The motion of the light relative to the background or to one's own field of view can help the pilot determine whether or not a collision can be ruled out. It is particularly helpful to analyze the problem in terms of the "fixity-of-bearing" criterion: when two aircraft are flying straight, constant-speed courses (not necessarily level) toward a collision, the bearing of either aircraft remains constant in the field of view of the pilot of the other. The criterion is not usable if the conditions are not met or cannot be assumed to be met, and thus is not applicable in terminal areas, where it is likely that a sighted aircraft will be in a maneuver; under any conditions, "fixity-of-bearing" must be used with reservations. Calvert (1958) has penetratingly analyzed this criterion, with important implications both for its limitations and for the approach to analyzing the usefulness of any technique.

One commonly used premise underlying analyses of collision probability is that there exists some required "warning time," admittedly uncertain, and variously estimated by different sources. Laufer (1955), in emphasizing the complexity of determining warning time, says that in "some exceptional cases a full minute or more may be required." He carries out his collision analysis for two warning times, 25 and 50 seconds. Another source (Honeywell Aeronautical Division, 1961) says, "Depending upon maneuverability of the aircraft, the desired minimum warning time generally accepted is 10 to 20 seconds." Stone (1954), thinking in terms of DC-7 aircraft, said "...we are now down to 15 seconds to avoid collisions." Projector & Robinson (1958), referring to Laufer (1955), said that the "required warning time probably lies between 25 and 50 seconds." Many illuminating engineers have pointed out (Laufer, 1955; Projector & Robinson, 1958, for example) that the light intensities required to furnish the required warning times, as estimates, under the full range of VFR conditions, were so high as to be impracticable. It has thus been recognized that visual collision avoidance, with presently available techniques and equipment, has serious limitations when closing speeds are high or flight visibility is near the VFR minimum.

Calvert's (1958) analysis shows, however, that there are other and more profound limitations. His analysis, although limited to the fixity-of-bearing criterion, has much broader implications, which apply generally to all avoidance techniques currently in use. Calvert bases his approach on how well a pilot can estimate the probability of collision and, in the

event he undertakes an avoidance maneuver, how assured he can be that the maneuver he selects will eliminate or at least reduce the probability of collision. The analysis shows that the uncertainties inherent in the fixity-of-bearing criterion are so great that the pilot often cannot use it effectively. In many situations, including some with moderate-speed aircraft, the information he needs to use the fixity criterion properly is unavailable or inadequate. If he does undertake an avoidance maneuver with inadequate information, he cannot tell what effect it will have on the probability of collision. Once he has begun the maneuver, he is committed, but he no longer has the fixity criterion, nor can he know when to end the maneuver. Since the uncertainties increase with distance, very early warning is sometimes of little or no help to him.

Because of the limitations on when it may be applied at all, and the inherent uncertainties when it is applicable, the fixity-of-bearing criterion, it seems evident, will not suffice as a visual collision-avoidance technique. It is often useful for roughly determining that an aircraft is not on a collision course; in other cases it is not applicable at all, or cannot be relied on.

Sector Information

All systems now in use present sector information. Position lights, as called for in the CAR, identify three azimuthal sectors around the aircraft: the red wingtip light identifies the sector from dead ahead around left to 110°; the green wingtip light identifies a similar sector on the right side, the white tail light identifies the remaining 140° to the rear. Some systems provide quadrantal coding, and others divide the azimuthal plane into six sectors. In some cases the sectors are sharply defined, in others the boundaries are vague.

It has always been supposed that sector information is essential and can be used by the pilot to determine collision probability, although how he might do so has not been clear. When carefully analyzed, it turns out to be impossible for a pilot to make such a determination except in very crude terms. The possibility of collision can sometimes be ruled out with the aid of sector information, but in large numbers of cases it is not possible for a pilot to use sector information to determine collision hazards.

To show why this is so, it is useful first to indicate how sector information can be used for crude screening. Optimally a sector-coded light system should accurately identify four quadrantal sectors in two modes, left vs. right and front vs. back. With such a system, no collision impends if:

1. The left side of the intruder aircraft is sighted on the left;

2. the right side of the intruder aircraft is sighted on the right;

3. the rear of the intruder aircraft is sighted to the rear.

An example of the use of these rules is illustrated in Fig. 1. If an observing pilot sights an aircraft to his left in one of two aspects, A or B, as shown in the figure, he may use quadrantal sector information to determine that aircraft B is not a collision threat by rule 1 above, since he sees its left aspect to his left. Aircraft A, on the other hand, showing its right aspect on the observer's left, may be a threat, and will require further attention.

It will be noted that the position light system called for by the CAR, with taillight coverage that is symmetrical to the rear, does not provide information that would distinguish these two cases.

This screening process is uncertain if either aircraft is turning (although in some cases, the turn may result in an indicated sector change early enough to warn the pilot).

The quadrantal sector system can be used to obtain other important information, but again only broadly and imprecisely. In evaluating a collision threat, the pilot finds it helpful to know the closing speed of his own aircraft and the intruder. If it is low, and the sighting distance reasonably large, he has time to continue observing in an effort to evaluate more precisely. If the closing speed is high, he must decide more quickly. A quickly made decision is subject to greater uncertainty and much higher probability of an unnecessary avoidance maneuver, especially if the pilot acts conservatively. For example, if a pilot sees an intruder ahead of him and identifies the intruder's light signal as the forward-aspect signal, he must assume a relatively high closing speed. If in the same situation he identifies the rear sector of the intruder, he may assume a lower closing speed, and consequently more time to decide. Because of the uncertainty of some of his information, neither determination can be very precise. While he knows his own speed and direction precisely, he does not in general know with any exactness the speed, relative bearing, or distance to the intruder, all of which would be needed, in addition to some difficult computations, to determine the time he has available before possible collision.

Another situation in which quadrantal sector coding might provide additional information is one, for example, in which

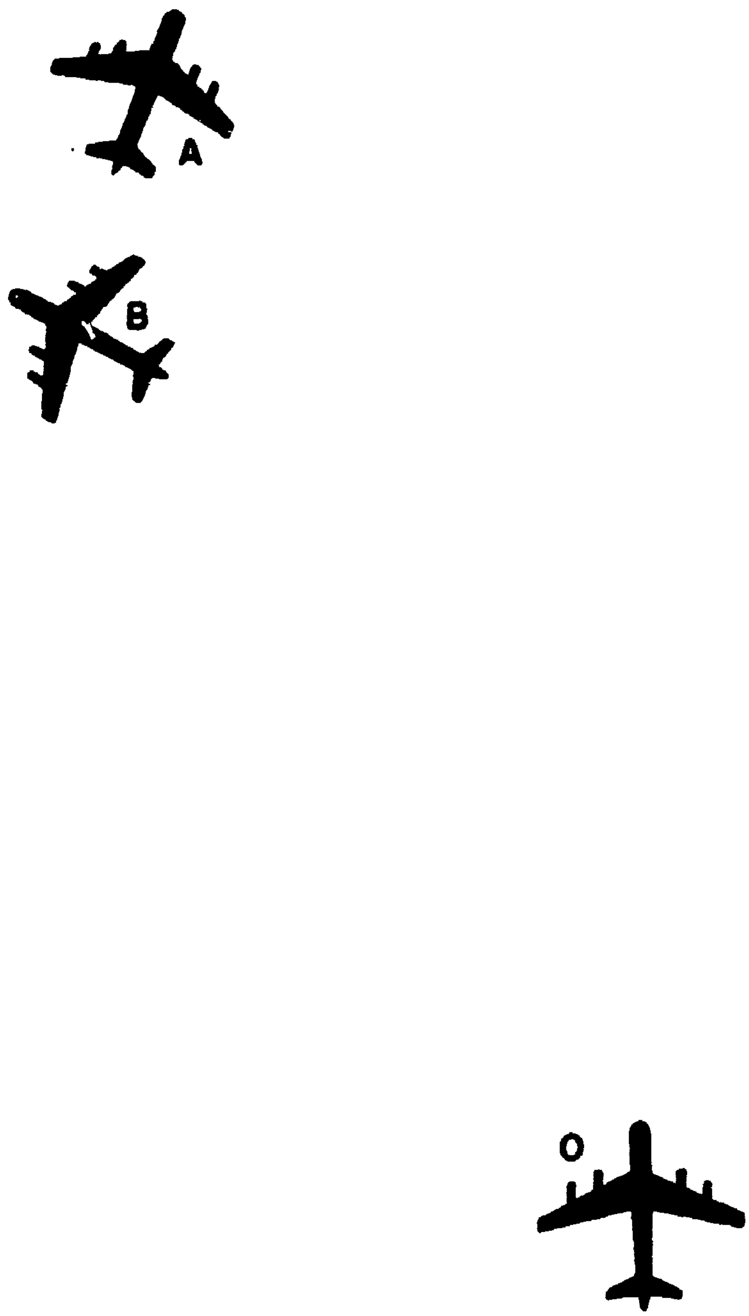

Fig. 1. Illustration of use of quadrantal sector coding to distinguish non-threats from possible threats. Observer, O, sees B's left on his left and classifies him as a non-threat. A shows his right aspect on O's left and is classified as a possible threat.

the intruder is sighted on the left, slightly ahead of a 90-degree bearing. If in such a sighting the right rearward quadrant of the intruder is signaled, the observing pilot may consider two possibilities: (a) the high probability that the intruder is on a diverging course and there is no danger of collision, (b) the smaller probability that the intruder is on a converging course. Even if it were the latter, the convergence would necessarily be relatively slow, since the angle of convergence can be no greater than the angle that the intruder sight line makes with the left abeam direction. If the pilot is satisfied that the intruder is not very close to him, he can reasonably decide to continue observing for a while in order to improve the precision of his determination of the existence of a collision hazard.

In principle, the kind of collision-probability analysis described above can be sharpened by a light system that defines more than four sectors. One might design an 8-sector system which divides each quadrant into two 45-degree sectors. The rules for categorizing threats and nonthreats could then be extended. However, there are limitations on the gains that might accrue:

1. Added complexity of the signal system would make analysis more difficult, and more subject to error and uncertainty.

2. Engineering coding techniques to identify as many as eight sectors would be difficult. For example, color coding is limited to four colors if reliable distinctiveness is to be achieved.

3. The remaining and unavoidable imprecisions of the technique (as described above) seriously limit the usefulness of such additional information.

Because of these limitations, it might be preferable to supply additional information in altogether different forms.

Thus, it is felt that a four-element quadrantal system provides crude but readily useful information, and should be considered the minimum for an effective sector-coded system. Gains in precision afforded by finer sectoring are likely to be offset by the difficulties of design and use, so that the quadrantal system may be considered optimal.

Sector information can be supplemented by additional visual cues apart from those coded into the light system. These include the intruder's motion relative to the background and relative to the observing pilot's frame of reference (the fixity-of-bearing criterion mentioned earlier), altitude difference as suggested by the angle of elevation

of the sight line to the intruder, and both distance and change of distance as estimated, however crudely, by observing the apparent intensity of the observed lights, etc. To utilize sector-coding information and supplemental cues with maximum efficiency, pilots must be trained to extract the essential information quickly and accurately, and they must be thoroughly aware of the limitations and uncertainties of this information.

In terminal areas, the information is likely to be of better quality than on airways, since speeds may be presumed generally low, even for high-performance aircraft, and the visual cues richer and more precise.

Other Information

Additional items of information that might be coded into a navigation light system are: (a) range; (b) speed; (c) identification of aircraft or aircraft type; (d) attitude (pitch or roll); (e) maneuver; and (f) altitude.

Range. As noted previously, secondary visual cues, such as motion relative to the background, or apparent intensity of lights, can help pilots make crude estimates of range. Reliable estimates based on apparent intensity would require standardizing both the intensity of various models of the same equipment and the distribution of intensity around the aircraft. Intensity distributions of most lights vary markedly with angle of elevation, and some vary in azimuthal distribution. The pilot is unable to estimate precisely the angle within the distribution. Also, as discussed below, the attenuation of intensity by the atmosphere varies widely over the range of transmissivities possible in VFR flight. Therefore, apparent intensity as a source of range information is unreliable. However, within limited conditions, pilots can estimate range fairly well, especially after some training. This was shown in ground-to-air and air-to-air tests of pilot ability to estimate range (Applied Psychology Corporation, 1962c). Lights can be coded to aid in range estimation by array coding or intensity coding, but this is either infeasible or unreliable, as will be shown in the discussion of coding techniques. Range coding in a lighting system therefore appears impractical.

Speed and identification. It would be useful to a pilot to know the speed of a sighted aircraft, but only for estimating the approximate order of magnitude of his decision time. Precise analysis would require precise knowledge of speed, plus sector information and a fairly difficult computation. Since the complete operation requires far more information than could conceivably be coded into lights, and, as well, difficult computation, such precise analysis seems infeasible. Nevertheless, it is both useful and feasible to attempt a rough bracketing of

closing speed. Sector coding permits this to a limited extent. Knowledge of speed would improve the estimate. A light code that would indicate speed therefore seems worth considering. This could be in the form of an automatic device that would code a light signal from an airspeed indicator. A second technique might identify aircraft type and thereby indicate a probable speed bracket. For example, identification by type might identify helicopters and small aircraft as a slow-speed group, larger propeller-driven aircraft as a medium-speed group, and high-performance jet aircraft as a high-speed group.

Because of its limited usefulness and residual uncertainty precise speed coding is probably not worthwhile. It may be that the limited information potential of lighting systems will make other types of coding preferable.

Attitude and maneuver. Attitude and maneuver are grouped together because they indicate some change in the course of the sighted aircraft from straight and level flight. Pitch information is not considered useful or feasible, since, except for extreme dive or climb, variation of pitch is too small to be reliably indicated by lights and is not related in a simple way to change of course. Turns and banks are feasible for coding into a light system, and it would be useful for a pilot to know that a sighted aircraft is engaged in or about to engage in such a maneuver. To a more or less limited extent, some existing systems provide such information. When both wingtip position lights are visible, and separable, the pilot has a fairly good indication of a banking maneuver. However, in a well-defined quadrantal system, quadrant cutoffs are relatively sharp and the overlap zones between quadrants too small to provide this information in other than very limited directions. Information as to maneuver--left or right turn, climb or descent--is generally useful, and should be considered as one of the kinds of information that could be coded into light systems.

Altitude. The remaining item of information that may be coded into the light system is altitude. It has been suggested that a light system indicating angle of elevation constitutes a kind of altitude-coded system. However, in the absence of range information, the triangulation required to convert angle of elevation to altitude difference is impossible. Thus the indications of an angle-of-elevation system, "same altitude," "above," or "below" are unresolvably imprecise.

A true altitude-indicating system, altimeter derived, does offer information which may be of considerable value. A detailed discussion of various types of altitude-coded navigation light systems, their probable advantages, and the practical problems to be solved is contained in Applied Psychology Corporation

Technical Report No. 1 (1961a). They are summarized below.[1]

Altitude-coded light systems can identify predetermined altitude segments such as 500, 1000, or 2000 feet. Conceivably the system segmentation could vary with altitude; for example, 500-foot segments could be used at low altitude, 1000-foot segments at medium altitudes, and 2000-foot segments at high altitudes. The altimeter transducer may be set to produce, for example, a light signal to identify a 1000-foot segment at 12,000 feet whenever the indicated altitude is anywhere from 11,500 to 12,500 feet.

Any practical system would be cyclic, the code system repeating after a given number of consecutive segments. If, for example, 1000-foot segments were identified in a 5-segment cycle, the indications for 6000, 11,000, 16,000 feet, etc., would be identical.

The advantage of altitude coding is that it identifies a fixed segment of the atmosphere. Unlike other information available to the pilot, it is not indeterminate because other information, such as range, is lacking. No matter what the sighting range, the quality of the information is the same. An avoidance maneuver can be undertaken at any time, requiring only that the pilot attain a fixed altitude separation. The pilot continues, during his maneuver and at its end, to have information enabling him to determine when avoidance has been safely effected. While some ambiguity is possible in a cyclic system, it leads only to an occasional unnecessary avoidance. It does not, as in the case of other techniques, result in a situation in which the uncertainties include the possibility that the avoidance maneuver has not been successful.

One possible advantage of altitude coding is that it may aid in estimating range. It was shown that estimating altitude difference from an angle-of-elevation observation is an indeterminate triangulation problem. But if the altitude difference is given by altitude-coded lights, the range is no longer indeterminate. Even though the altitude information is still approximate, it may significantly improve the accuracy of range estimates over what they would be without any altitude information.

Designing altitude-coded systems presents a number of other problems.

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1 The results of studies of the usefulness of altitude-coded navigation lights are contained in Technical Reports Nos. 8 and 16 (Applied Psychology Corporation, 1962b, f).

Inaccuracies are unavoidable. In addition to the inherent inaccuracies of presently available altimeters, which are a serious problem in all methods of collision avoidance relying wholly or partly on altitude separation, there are bound to be errors in transducing altimeter information into the coded light signal.

Since only altitude segments are identified, there is some uncertainty about precisely where in a segment a sighted aircraft is located. The top of one segment is at the same altitude as the bottom of the next higher segment, and a one-segment separation may not be a certain indicator of safe separation.

Rules-of-the-road would have to be designed to utilize the altitude information and would have to be tailored to the particular system used. It would be necessary, for example, to insure that two aircraft on the same altitude did not engage in the same altitude avoidance maneuver.

In a complete navigation light system, it would be possible to include other information in addition to altitude information. One combination might be altitude and sector information.

Summary

Four kinds of information codable into navigation light systems may be of value in avoiding collision. They are:

1. Sector information. An optimum system should identify four quadrantal sectors fairly precisely. While sector information is not as useful as has been supposed, it does have some utility for roughly categorizing aircraft into "threats" and "nonthreats." It is also useful in terminal areas in determining the course and future location of sighted aircraft.

2. Altitude information. Altitude information might enable a pilot to improve considerably his ability to control the outcome of a collision threat, in many cases with a degree of certainty not attainable with other information. It has other possible advantages that suggest it is well worth investigating.

3. Speed information. Such information would be useful to some extent. It is doubtful, however, that it would be advantageous to identify more than two or three categories of speed, for example, slow, medium, fast. The speed code could be derived from the airspeed indicator or could identify aircraft type by maximum cruising speed.

4. Maneuver information. Indicating a change of course, either turn or change of altitude, would be helpful in warning

a pilot that his judgment based on other information or cues is subject to change.

In addition to the information obtained from coded lights, the pilot can obtain useful information from any sighted aircraft light. This includes, of course, the presence and sight bearing of the aircraft. It also includes the use of the fixity-of-bearing criterion and, through secondary visual cues such as movement relative to background, some capability of determining the course of the aircraft and the existence of a "threat."

A system that would code all four types of information would be complex, difficult to use, and probably impracticable on the basis of engineering, economic, or human capability considerations. There is, however, a strong possibility that the present "standard" system calling for sector coding could be modified to supply quadrantal sector coding, and that it would be worthwhile to supplement this with at least one of the three remaining information types. Of these, altitude coding seems most promising.

III. LIGHT CODING TECHNIQUES

Five more-or-less distinct methods of coding information into light signals may be defined: (a) color coding, (b) flash coding, (c) flash-frequency coding, (d) flash-pattern coding, (e) intensity coding, and (f) array coding.

These may be combined in a great variety of ways, so that in principle the information-conveying capability of navigation light systems is very large.[1]

Each technique has its own distinctive characteristics, often complexly related to the over-all problem of visual collision avoidance. In assessing the usefulness of a light-coding technique, several factors must be considered: (a) the speed and (b) the accuracy with which the code can be read; (c) the amount of information that can be coded; and (d) the effect of the code on other aspects of operation.

Color Coding

The earliest technique applied to navigation light systems, and still the most widely used, is color coding as prescribed for use in the current CAR position light system. These colors are codified and their precise definitions given under "Aviation" colors in Federal Standard No. 3, 1951.

Three-color coding systems are in widespread use in other fields as well as aviation (highway traffic signals, for example) and there is little doubt the 3-color systems provide a high degree of reading accuracy and speed, and fairly good efficiency with standard light sources and filters.

A color-coded system with more than three colors presents difficulty. Federal Standard No. 3 defines five Aviation colors: red, yellow, green, blue, and white, but these colors

> ...are intended for high-intensity long-range signal lights in which the primary consideration is that the light be seen, the secondary consideration is that its color be identified. If aviation colors are used in situations requiring positive color identification, relatively few colors are used at a time. For example, aviation white is not intended to be distinguishable from aviation yellow unless it is in juxtaposition with it.

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1 Combination codes will be discussed as a seventh type of coding.

The Federal Standard goes on to define a second category of "Identification" colors: red, yellow, green, and lunar-white (a bluish white color). In order to insure reliable distinctiveness the specificationlimits for this series of colors are much narrower than for the Aviation series. It is thus implicit that the Federal Standard is written with the idea that a four-color system is the maximum for reliable distinctiveness, and even here, color specification tolerances are small, with a consequent reduction in luminous efficiency.

The difference in the specifications for the two series of colors is indicated by the minimum transmittance limits for comparable glassware, as shown in Table 1.

McNicholas (1936), who extensively investigated the best colors for use in a railway signal system, found that a set with color names "red, orange-yellow, white, green, blue, and purple" was the optimum set of six. For various reasons, including the requirement for reasonable tolerances in specifying color filters, the need for high efficiency in producing specified colors, the unsuitability of blue and purple for distant signals, and the residual confusability between adjacent colors in McNicholas' 6-color system, it is evident that six colors are too many for aircraft navigation light systems.

Hill (1947) experimented on the distinctiveness of 73 widely distributed colors. The results indicate the reliability with which his subjects identified the test colors as red, green-blue, orange-yellow, and white, when the signals were presented at low levels of intensity. The data are helpful in establishing boundaries for color signals in aircraft navigation light systems.

Three-, four-, five-, and six-color systems are discussed in an Annex to Recommendations by the Technical Committee on the Colors of Signal Lights of the CIE (1955) and in subsequent formal recommendations (CIE, 1959). It is suggested that a three-color system be considered maximum for general application. A four-color system is described and specified, but it is suggested that the yellow and bluish white will not be adequately distinctive for distant viewing at low illumination. The four colors recommended are red, green, yellow, and bluish white, more or less as described in Federal Standard No. 3.

Another problem in color coding is color deficiency in pilots. Part 29 of the CAR requires normal color vision for a first-class medical certificate. Pilots with second- and third-class certificates are required to be able to distinguish aviation colors, red, green, and white. A few such pilots may

Table 1

Minimum Transmittance Limits for Two

Color Series Specified in Federal Standard No. 3

Color	Minimum Transmittance	
	Aviation Series	Identification Series
Red	.175	.048
Green	.200	.048
Yellow	.500	.400

have difficulty in distinguishing the colors of a four-color system.

It may be noted here that color distinction can be considerably more precise than suggested above if colors are seen not in isolation but close together in space or time. For example, yellow and bluish white may be somewhat confusable if either is seen alone, but if both colors are seen side by side, or if they are seen in rapid succession, they are readily distinguished. Under such conditions, systems with four or even more colors are entirely practicable. It should also be noted that the precision of color distinction in any color system is poor when signal lights are at or near threshold. With any color system, but particularly with higher order systems, there is a region near threshold where even though signal lights may be detected color distinction may be impossible or uncertain.[1]

In summary, three-color systems provide good color distinction, are quickly and accurately read if not too near threshold, and can be designed with fairly good efficiency. (Aviation red and green glassware with transmittances of the order of 20% are readily available for use with incandescent lamps.) If four colors are required in isolation, color coding is less distinctive, and it may be necessary to restrict the tolerances of the colors to minimize confusion.

Flash Coding

Light signal flashes may impart information as well as increase the efficiency of utilization of electrical energy to produce visibility. The distinction between flashing and steady lights is used in one version of the navigation light system described in the current CAR, wherein the "anti-collision" light emits an omnidirectional flashing red signal while the left wingtip position light emits a steady red signal identifying the left forward sector.

Since lights may be flashed in a variety of ways, this technique is versatile. Flashes may be distinctive because of their on-off ratio, frequency of flashes, grouping of flashes by varying successive dark intervals, or because of the use of sequences of long- and short-duration flashes (dots and dashes).

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1 An excellent detailed critical review of research work on color-identification systems may be found in Breckenridge, 1960. A discussion of the properties of signal color systems and their uses and specification may be found in Breckenridge, 1962.

The fact that a light is flashing can be determined fairly quickly, usually by the time two or three flashes have been observed. Flash patterns can usually be identified by the time two or three cycles have been completed. Flash characteristics are not as rapidly identified as is color at intensity levels well above threshold. On the other hand, color identification near threshold is often very difficult or impossible, when the flashing characteristic is still identifiable. At threshold the flashing characteristic is not distinctive, because even steady lights appear to twinkle or flash.

The dark interval between light flashes, especially if of appreciable duration, can be troublesome. Occasionally it may delay pickup of the intruder aircraft, if the pilot's center of attention happens to pass the target while the signal light is in the dark phase. The flashing characteristic is also an impediment in the use of the fixity-of-bearing criterion (Applied Psychology Corporation, 1961a). The inherent uncertainty in a pilot's ability to detect fixity directly affects the precision of his determination. There is little data available on the threshold detectability of movement for steady signal lights. In ideal laboratory situations movement rates of the order of 1 minute of angle per second are detectable (Leibowitz, 1955), but detection thresholds in operational situations are undoubtedly much larger for steady signals, and larger still for flashing signals.

Flash-Frequency Coding

Different flash frequencies may be used to code information into a navigation light system. Two frequencies are used in a system proposed by the Lytle Engineering and Manufacturing Company[1], and three frequencies in the "Honeywell-Atkins Maximum Safety Light" (Honeywell Aero Div., 1961). In both, flash frequencies identify azimuthal sectors around the aircraft.

Sperling (1961) has shown in a closely controlled laboratory experiment that observers can discriminate well among three flash rates--40, 80, and 160 flashes per minute--if the signal is not too close to threshold. At and near threshold, discriminability was poor and there was a tendency to interpret both the lower frequencies as the highest. Robinson (1959), conducting a flight test of several navigation light systems,

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[1] According to information supplied to Bureau of Aeronautics, Department of the Navy, Oct. 1957 by Lytle Engineering and Manufacturing Company.

including the Honeywell-Atkins, found that occasionally the 80 FPM frequency was read as either 40 or 160. In particula when the presentation of 80 FPM was preceded by either the slow or fast frequency, the error tended toward reading the medium frequency as the extreme frequency at the other end of the scale. Signal intensities were well above threshold. It should be noted that the observer's task was interpreting information coded into the signals, so that errors included errors in interpretation as well as errors in reading the flash frequency. Gebhard (1948), after some preliminary observations, suggested that only 15 discriminable steps exist between 30 and 1800 FPM, but in later work (Gebhard, 1949) found only six identifiable rates between 120 and 2100 FPM. The entire upper range of these studies must be considered unavailable for navigation light systems, because of engineering difficulties and also because they are in the range of flicker fusion for the intensity levels important in collision avoidance. Cohen and Dinnerstein (1958) concluded that no more than five discriminable rates may be used betwee 15 and 720 FPM.

It seems unlikely that more than three, or at the most four, frequencies could be used in navigation light systems, and that even this small number might result in reading errors of some consequence.

The time required to "read" frequencies in such systems will vary with the frequency, and at the lowest may be appreciable. At a rate of 40 flashes per minute, for example, using the criterion that at least 3 flashes will be required for discrimination, it will take nearly 5 seconds to come to a decision with confidence. However, it may be possible to identify 40 FPM (in a system consisting of three frequencies, 40, 80, and 160 FPM) by eliminating the higher frequencies well before the third flash at 40 FPM is seen.

Flash-Pattern Coding

The most versatile technique, flash-pattern coding, is almost unavoidable if large amounts of information must be coded into a light system. Three proposed navigation light systems flash in such a way that successive dark intervals vary in duration, the difference indicating sector. Projector (1959a) has proposed a system in which a dot-dash code identifies the left side of the aircraft and a dash-dot code the right side.

The use of various sets of dot-dash signals, a standard technique for communicating information in military and other applications, may be considered for navigation light systems. One version is the "continuous" presentation, which omits the distinctively long dark interval between groups, with all dark

intervals uniformly short in duration. An example would be a dot followed by a dash, with this sequence repeated immediately, without separation. Continuous presentations reduce the number of distinctive codes which are practicable--there is no difference, for example, between dot-dash and dash-dot--but have the advantage of eliminating the long dark interval. Another variation is the use of groups consisting of two or more subgroups. For example, a group may consist of a single dot, a long interval, and then a dot-dash, etc.

Flash pattern coding has been investigated by Cook and Beazley (1962). Three sets of signals were tested: 12 Morse code letters, 12 continuous signals, and 12 signals consisting of various arrangements of dots alone, including several of the subgroup type. The 12 Morse signals all consisted of 2 or 3 elements. Two of these were repeated in the set of 12 dots-only signals. The three sets of signals were evaluated both as sets of 12 signals and as individual signals, in terms of the time required to learn them, the accuracy with which they were read, and the time it took to read them. The continuous set of signals was found inferior to either of the other sets in regard to all three criteria. Apparently the pause between signal groups is helpful to the observers in reading the codes. Eleven of the Morse code signals and 6 of the dots-only signals were judged as constituting effective sets for a system.

While there are as yet no experimental data on which to base further selection of useful codes, some additional considerations may be helpful. In the test, the interflash and dot duration was .15 seconds, and the dash and intergroup (or intersubgroup) durations were .45 seconds. On this basis, the longest complete cycle in the Morse code set, three dashes, was 1.80 seconds. Two of the selected dots-only signals required 2.70 seconds per cycle. The two next-largest durations were 2.10 seconds. It is thus apparent that the cycle times for the Morse code set are appreciably shorter than those for the dots-only set.

It also appears likely that the Morse code set, especially if restricted to signals containing both dots and dashes (reducing the selected number to nine) may be more distinctive against city-light backgrounds. Many lights in such backgrounds flash either regularly or erratically. It is unlikely, however, that any background lights will be seen to flash in a regular code consisting of both dots and dashes.

The Morse code set (with only those symbols consisting of dots and dashes) thus appears to be superior to the dots-only set because (a) it contains many more usable signals; (b) the time required to present complete cycles of its codes is generally much shorter; and (c) it is likely to be more distinctive against background lights.

Intensity Coding

Signal lights can convey information through differences in intensity. For example, any light seems to grow less intense with increasing distance, and a more intense light may be seen further away than a less intense one, providing some clue to distance. Anti-collision lights are generally more intense than position lights, so that in most cases one may infer that if only the anti-collision light can be seen, the aircraft is farther away than if both the anti-collision light and a position light are visible.

Unfortunately a number of factors limit the value of this kind of information. One of the most important is attenuation of light as it passes through the atmosphere. Figure 2 shows the range in miles at various transmissivities of the atmosphere for three signal light intensities. These curves are based on an assumed "practical" threshold illumination of 0.5 mile-candle. The three signal intensities, 20, 100, and 500 candles, represent approximately the order of magnitude of low-, medium-, and high-intensity lights in present-day navigation light systems. The 3-mile VFR visibility requirement corresponds approximately to an atmospheric transmissivity of 0.25/mile. It is evident from the figure that range estimated from apparent intensity is subject to considerable ambiguity, if the atmospheric transmissivity is unknown. For example, when the transmissivity is 0.85/mile ("very clear") a 20-candlepower signal observed about 4 miles away would appear equal in intensity to a 500-candlepower light observed at the same distance when the transmissivity is 0.4/mile ("light haze"). Or, to look at it another way, a 100-candlepower light signal would appear at the "practical" threshold when it is nearly 8 miles away, if the transmissivity is 0.85/mile; but if the transmissivity is 0.4/mile, it would appear at the "practical" threshold at less than half that distance.

The appearance of signal lights is very sensitive to atmospheric transmissivity, even within the limited range of VFR. Pilots can estimate the condition of the atmosphere from visual cues, from weather reports, etc., although such estimates are often subject to considerable uncertainty. Because of the value of range information, pilots should be trained to make such estimates, however uncertain they may be. Studies have shown that ability to estimate range can be greatly improved by training (Applied Psychology Corporation, 1962c).

Another factor tending to reduce reliability of range information derived from signal lights is the variability of intensity, both within the distribution of any given light as the sighting direction changes, and between different lights.

If signals of different intensities appear simultaneously

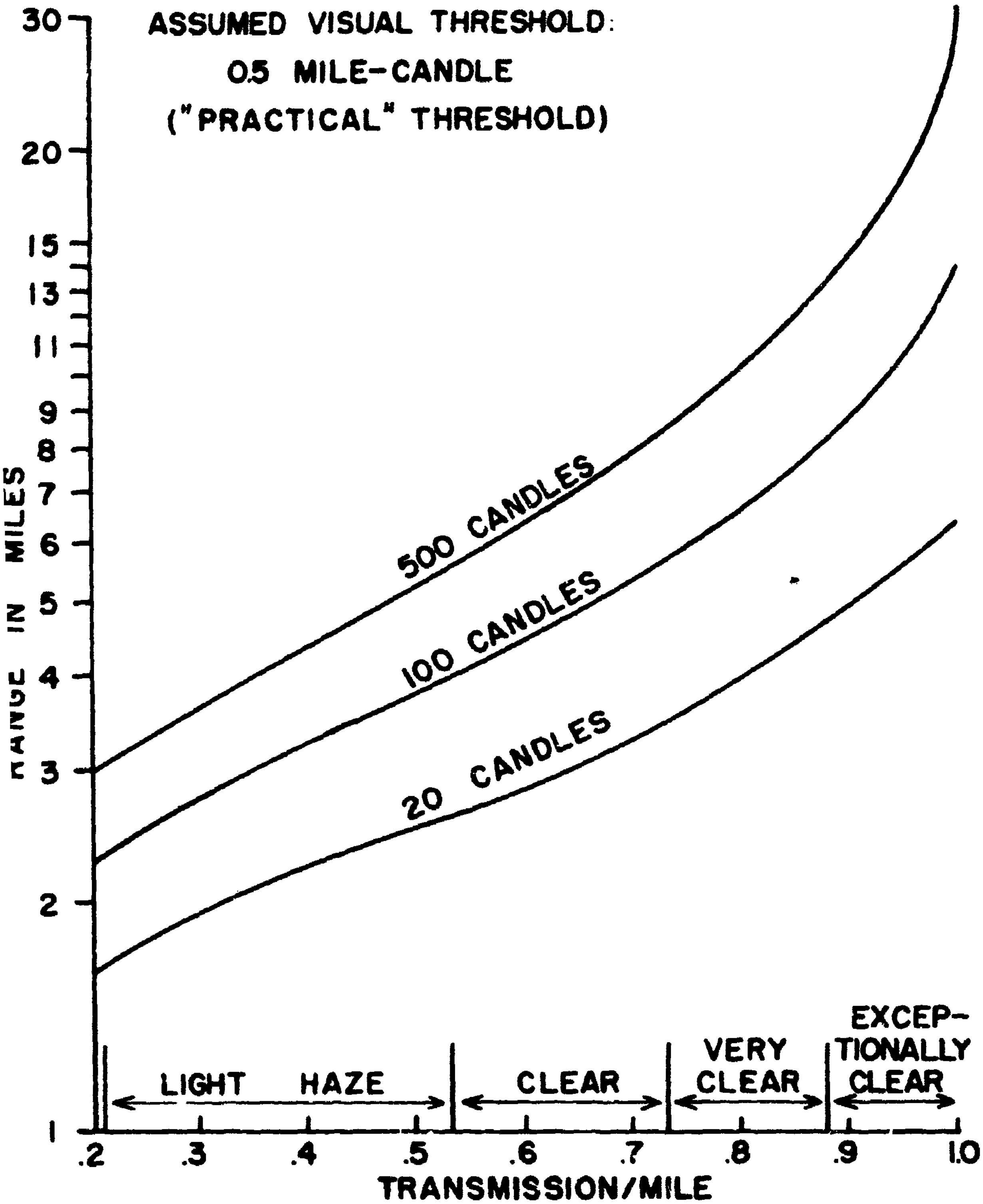

Fig. 2. Range vs. atmospheric transmissivity for light intensities of 20, 100, and 500 candles, based on "practical" illumination threshold of 0.5 mile-candle. (A "mile-candle" is the illumination at a distance of 1 mile produced by a source with an intensity of 1 candle.)

or in close succession, the pilot's ability to estimate range may be somewhat improved, although the results of a laboratory study of such a system do not support this (Applied Psychology Corporation, 1962d). If two intensities are used, each has a separate threshold and corresponding range. Some anti-collision lights, for example, have alternating flashes of different intensities. When picked up near the limiting range, only the higher-intensity flash is visible, and the flash frequency is half the nominal frequency. Close in, the weaker flash is seen and the frequency doubles to nominal frequency. In addition to the change of frequency, the difference in intensity between successive flashes is noticeable. The anti-collision lights with alternating flashes of different intensities are good examples of the kind of unreliability of this distance estimation technique, mentioned above. The higher intensity flash is achieved by optics which at the same time produce much narrower vertical beam spread. Thus the beam which is higher in intensity near horizontal is lower in intensity at elevation angles greater than about 5 or 10 degrees. If the sighted aircraft is in a bank, and only one of the two beams is visible, it might be interpreted that the aircraft is at a great distance when in fact it is very close by.

Intensity coding may help to refine judgments of range, but does not overcome the inherent difficulties described previously. It may be that such coding together with training designed to make maximum use of its potential can result in significant improvements. The training should include estimating atmospheric transmissivity, to minimize the uncertainties contributed by this factor. Possible improvement with training in estimating range has been shown in both ground-to-air and air-to-air tests (Applied Psychology Corporation, 1962c).

Intensity coding can be used to convey other information, particularly if two or more intensities are presented together in a spatial array or close together in sequence. Visual estimates of intensity are very uncertain, but comparative judgments can be fairly precise. However, spatial arrays of intensity-coded lights are not considered to be of value.[1] Sequential arrays may be useful. It is felt that such coding should be reserved for estimating range, since (a) this is an important item of information, (b) no better techniques for providing it have been found, and (c) the connection between apparent intensity and range, even if subject to uncertainties, is a close one.

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1 This will be discussed in the section on array coding.

Simple intensity codes can be read quickly. Estimates of apparent intensity are direct and immediate. If a sequential code is used, there is an inherent delay in presenting the time sequence, but the delay can be quite short since the time required for each element in the sequence need not be long.

Array Coding

Spatial arrays of lights may convey information, and offer attractive possibilities of conveying detailed information rapidly. The technique has been used as a major or incidental component in a number of navigation light systems.

Static spatial arrays, if not too complex or ambiguous, convey their information very rapidly. Those which build up the array in a time interval may be somewhat slower but are still quite rapid if the time interval is short. In the Madsen system, for example, the time to complete a flashing sequence is about 1/6 of a second, and the repetition rate (for a single row) is 40 per minute.

However, several difficulties in the use of array coding limit its usefulness.

Spatial arrays vary in apparent size with the distance of observation. Arrays whose angular dimensions are of the order of one minute of arc or less will be difficult to interpret, especially if they are complex. Thus if an array's cross-sectional diameter is 6 feet, it will subtend 1 minute of arc at a range of about 4 miles. While it is sometimes possible to locate the elements of an array in such a way as to obtain dimensional cross-sections of 6 feet or more, often it is difficult or impossible.

For example, in the systems using rows of sequentially flashed lights along the fuselage, adequate dimensions are obtainable along the fuselage when the observer is abeam, but as the direction of observation is moved to the front or rear the row of lights is foreshortened until it becomes unreadable as a row. The precise limit of readability will of course depend on the length of the row and on the distance and angle of observation.

Arrays are much more feasible when the information is intended for use in limited directions. If the direction of interest is abeam, the length of the fuselage is available for the array. If the direction is fore or aft, the wingtips provide adequate separation. If the view is from above or below, both the fuselage and wings provide potentially large cross section.

If the kinds of information coded into an array require that it have the same appearance for all directions of sighting, then array coding is likely to be altogether impracticable. If the array-coding system codes information by means of the change of the appearance of the array with direction, it is more practicable, in principle, to provide necessary locations about the aircraft, but usually at the cost of increased complexity. An example of such an array is the Lytle system, in which three flashing lights are mounted at the forward end of the fuselage, one at the nose,and two back along the fuselage, one on top and one on bottom. Head-on, the three lights are in a vertical line. On either side of head-on, the three lights form a triangle, the apex of which (at the nose light) indicates how far the view is from head-on. A similar arrangement at the rear, with the three rear lights flashing at lower frequency, completes the system. Sector information is provided to the side by the array and the flash frequency coding of the four fuselage lights. This system seems to provide excellent azimuthal sector information which is unambiguous and simple to learn. It also exemplifies many of the problems of array coding, including those already mentioned and others. These are listed, but similar problems are likely to arise in the design of any complete array-coded system.

1. From the point of view of backscatter, the three lights at the front of the fuselage are in the worst possible location. Of these three, the nose light and the one on top of the fuselage are in particularly poor locations for any appreciably intense light.

2. From several directions, one or more of the lights in any given array may be occulted by the wings, the empennage, or other structures. If one or more lights of an array is missing, the information may be uninterpretable or misleading. With any navigation light system, it is often difficult to avoid occultation in some directions, but when an array code is used the difficulty is compounded.

3. Precision is often degraded when the observer is not on the same altitude, even when the elevation angle is relatively small. Near dead ahead, for example, if the observer is at a lower altitude, the nose light and the upper forward fuselage light are closer together and may even merge, making the information difficult to read or ambiguous. If they are separable, however, the information may be adequate and may even give some indication of the elevation angle.

4. Locating the lights to provide adequate cross section at required distances poses a problem. Forward, for example, the maximum dimension is the height of the fuselage. On a very large aircraft this may be adequate. On small aircraft, it may

be quite inadequate. In general, the problem of obtaining adequate array dimensions on smaller aircraft is especially difficult to solve.

Under certain conditions some array-coded systems give misleading information. Those systems using sequentially flashed rows of lights to indicate the direction of flight may sometimes appear to flash in the opposite direction. This occurs if the observer's speed is greater than the projected component, parallel to the observer's direction of flight, of the sum of the intruder's speed and the speed of progression of the row of lights. In a typical installation (9-foot spacing, between lights of a row, .075 seconds between successive flashes) the speed of the lights is about 80 miles per hour. If the intruder aircraft carrying these lights has a speed of 200 miles per hour, the sum of the two speeds is 280 miles per hour. If the observer aircraft is abeam, moving on a parallel course at a speed of 280 miles per hour, the lights will appear to be successive flashes from a single light in a fixed position; if the speed is greater than 280 miles per hour then the direction of the successive flashes will appear to be opposite to the actual direction of the observer's aircraft. Although in such a relative-course situation no collision impends, the information is nevertheless misleading, and in other situations not so clearly noncollision, the false information could lead to serious confusion--if not to collision.

Some array codes use the standardized (CAR) location of navigation lights, for example on the wingtips. Occasionally this can operate satisfactorily, but here too may present problems. If both lights can be seen the wingtip array can convey banking information, but aspect information obtained from the array of a wingtip light and the taillight is more ambiguous if the intruder aircraft structure is unknown. The spatial relation between the wingtip and tail differs from airplane to airplane. On some the wingtip is well forward of the tail, on others much closer to it or even rearward of it.

Because of the difficulties with array coding, it should not generally be a primary part of a navigation light system. It may have incidental value in systems employing other types of coding.

Combination Coding

Most navigation light systems combine coding techniques. The CAR "standard" system codes azimuthal sectors by color and distinguishes the red anti-collision light from the red position light by flash coding and, to a lesser extent, intensity coding. (As with many other systems, incidental array coding of the wingtip lights gives bank indication in limited directions.) In the

Honeywell-Atkins system, flash-frequency coding provides azimuthal sector information, while the wingtip array, because of a sizable overlap (45 degrees on either side of fore and aft) gives bank information over a substantial field of view. The Lytle system uses flash-frequency coding and array coding.

Techniques can be combined readily, often without significant loss of distinctiveness for either type in the combination. Color coding combined with any type of flash coding can be read, except for any long, dark interval, with little or no more difficulty than if used alone. A system for presenting large amounts of different types of information would almost certainly combine techniques.

One way of adding information to a system is "time sharing," presenting different information in successive intervals, or distinguishing signals by giving them an alternating characteristic. One navigation light system, for example, has two tail lights, one red and one white, flashing alternately, thus distinguishing them from the left wingtip light, which is a simple flashing red light. Dot-dash flash pattern codes are similar to the red-white taillight, in that distinctiveness and information are gained by having successive flashes differ in some respect. The more important type of time-sharing combinations would present different information successively. No system using this kind of time-sharing has yet been formally proposed, and it is not likely to be advantageous unless very large amounts of information are considered essential.

Coding techniques can be combined in numerous ways, and the optimum combination for a given requirement may not be easy to choose. The choice requires careful evaluation in terms of the four criteria for individual techniques, listed at the beginning of this section, and must in addition consider interaction effects.

One particular combination is of special interest: flash coding and intensity coding. The discussion of flash coding noted that the fixity-of-bearing criterion to determine a collision course is likely to be much less accurate if the target light flashes than if it is steady. Such reduced precision can be avoided to some extent if the light pulsates rather than flashes, so that the signal may be considered to consist of a steady light and a superposed flashing light. The flashes, more intense than the steady component, provide intensity coding as described earlier. When first picked up, the steady component is invisible, and the appearance is that of a simple flashing light. As the distance is reduced, the steady component becomes visible and there are no dark intervals. Within the range that the steady component can be seen,

the fixity criterion should be usable with nearly as much, perhaps as much, precision as with a simple steady light. The difficulty in using fixity at longer ranges would continue in such a system, but is not too much of a loss because at longer ranges the usefulness of the criterion is not very great anyway (Calvert, 1958; Applied Psychology Corporation, 1961a).

IV. INTENSITY, EFFICIENCY, AND VISIBILITY

The visibility of a light signal may be defined in terms of the threshold illumination it produces at the observer's eye under a given set of conditions. This threshold is determined by a large number of physical and psychological factors, among which are (a) the signal's intensity, size and shape, color, movement, and distance from the observer; (b) luminance of the background; (c) other lights in the field of view; (d) the atmosphere; (e) backscatter; (f) the optical quality and location of the cockpit windows; (g) the portion of the observer's retina on which the signal image impinges; (h) the observer's adaptive state, physiological environment, individual visual capability, alertness, and search habits; and (i) distractions diverting the observer's attention.

This discussion will consider the more important aspects as they relate to optimum design and operational use of aircraft navigation light systems. Because of their special importance, effects of the atmosphere, backscatter, background lights, and cockpit visibility will be discussed separately in subsequent sections.

Navigation lights, because of their small size and the relatively large distances at which they are observed may be considered "point sources": only their photometric intensity need be considered in determining visibility. It has occasionally been proposed that extended sources be used in navigation light systems, either by using extensive light sources, such as linear sources installed along appreciable lengths of wing edges, or by floodlighting the surfaces of the aircraft; the floodlights themselves would be invisible generally but would provide a visible signal by illuminating the surface. As will be shown later, extending light signals into lines or areas drastically reduces the efficiency with which electrical energy is converted into visible light signals. Because of the need for high efficiency, navigation light signals should be limited to point sources.

Movement of a light signal in a field of view reduces its apparent intensity. If the movement is rapid, a signal may become invisible, although significant effects of movement on visual performance occur at rates far in excess of those involved in visual collision avoidance (Miller, 1958). However, movement may affect an observer's ability to detect a signal when the background contains other signals.[1]

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1 This is discussed in the chapter on Lights and Backgrounds.

Individuals vary considerably in all kinds of visual characteristics. It is not possible in this report to discuss this in detail; in general, only average performance is discussed.

Visual Thresholds

In the absence of atmospheric attenuation, the illumination, E, produced at an observer's eye, located at a distance, D, from a source of intensity, I, is given by the "inverse square law":

$$E = \frac{I}{D^2}$$

Thus the apparent intensity of a source of a given intensity seen at a given distance is the same as that of a source of four times the intensity seen twice as far away, if the two sources are alike in all other respects.[1]

The threshold illumination, E_o, has been extensively investigated, but the results vary over an extraordinarily wide range. Some variation is due to the considerable variability among individuals, and in any individual from time to time. Another source of variation is the uncertainty of the criteria used to determine threshold. Threshold judgments by observers are largely subjective, and are affected significantly by the instruction they receive as well as by the experimental design.

The reported results are also related to the scoring techniques. One commonly used method considers threshold that value of illumination at which the observer's accuracy score is 50%, a scoring criterion which theoretically has a number of advantages; but others feel that a threshold representing a higher likelihood of seeing is more meaningful, and thus use a scoring criterion of 90 or 95% accuracy.

The order of magnitude of threshold illumination for white point-source signals observed against dark backgrounds with a high probability of seeing under favorable conditions is 0.01 mile-candle (Knoll, Tousey, & Hulburt, 1946).[2] Actual field sightings with observers not knowing where or when a signal may appear occur at considerably higher threshold illuminations and are much more variable than those obtained or

1 A more detailed discussion of range is given in Chapter V.

2 The illumination produced by a source of intensity .01 candle at a distance of 1 mile in perfectly clear air, for example.

cited by Knoll, Tousey & Hulburt. For estimation and specification it is convenient to agree on some field value of threshold illumination which may be considered reasonably representative of search situations such as prevail in aircraft collision avoidance. Many experts in this area agree on a "practical" or "useful" threshold of about 0.5 mile-candle (Middleton, 1958, p. 99; Technical Committee 3.3.2.1, C.I.E., 1955; Stiles, Bennett, & Green, 1937, p.30; Gilbert & Pearson, 1951; Adrian & Jainski, 1960). While the "practical" threshold may be used for general calculation, very different thresholds may apply in particular cases (Koomen & Dunkelman, 1953).

The value of threshold illumination is not much affected by variations in background luminance in the range from total darkness to starlit sky; but as background luminance increases above this range, the threshold signal illumination increases by as much as 100 times greater than that against a very dark background (Middleton, 1958, p. 97f; Knoll et al, 1946; de Boer, 1951).

Adaptation, Fixation, and Signal Color

The adaptive state of the observer has a profound and complex effect on his visual capability. Measured in terms of ability to detect the presence of a faint signal, this effect may change the detection threshold by several orders of magnitude. The reduction in sensitivity caused by an excess of brightness in the visual environment is related to a number of factors, and in any given cockpit situation is likely to be difficult to analyze. In one investigation, cited by Stiles et al (1937), background adapting luminances from less than 10^{-3} (moonless night sky) up to nearly 500 ft-L (overcast sky) were utilized. The ratio of the sensitivity 1 second after the adapting luminance was turned off to the sensitivity after an hour of dark adaptation was determined. Ratios as high as 1000:1 were obtained. While the necessity for maintaining a minimal luminance level in the cockpit in order to carry our pilot functions precludes the possibility of attaining complete dark adaptation, carelessness in lighting the cockpit can easily produce disabilities in ratios ranging from 5:1 to 100:1 and gross carelessness can result in ratios considerably greater. It is thus of great importance that pilot's vision be maintained in as nearly fully dark-adapted condition as is consonant with performing other functions, and thus ambient illumination in the cockpit should be at a minimum.

Absolute dark adaptation, which requires a half hour or more in total darkness, is probably only rarely achieved under actual flight conditions. Intermediate states of dark adaptation are common and can be considerably affected by factors

subject to control within the aircraft. Ambient luminances outside the cockpit impose the basic limit on the extent of dark adaptation possible. (Backscatter from lights on the observer's aircraft may contribute significantly to ambient luminance.) However, high luminances in the cockpit may reduce the degree of dark adaptation or delay recovery of the fullest possible adaptation for appreciable lengths of time (Wulfeck, Weisz, & Raben, 1958).

Two types of receptor elements are distributed through the retina, the rods and the cones. In the fovea, the central part of the retina, cones are densely distributed and there are no rods. Cones are distributed through the peripheral or parafoveal parts of the retina, outside the fovea, but their density is very much less than in the fovea. When the eye is fully dark adapted only the rods are involved in sensing very faint lights. When the eye is light adapted, only the cones are involved in seeing. In intermediate adaptive states, both rods and cones may be involved. The cone system is largely responsible for sensing color and appreciating detail. Color cannot be identified when only rod vision is involved. When the eye is dark adapted the sensitivity of the rods is much greater than that of the cones for all colors except deep reds. The rod threshold for a faint green signal is of the order of 100 times lower than the cone threshold and approaches a value nearly 1000 times lower at the extreme blue end of the spectrum (Wulfeck et al, 1958).

With complete dark adaptation, it is thus possible to detect in the periphery faint green or blue signals which are invisible when the eye is fixated directly on the signal and its image falls on the fovea. It is, however, uncertain how important a role this plays in visual collision avoidance, since complete dark adaptation is seldom if ever achieved during flight. Signal illumination levels at which sighting actually occurs are likely to be well above the levels at which pure rod response prevails. Middleton (1958, p. 98) says the pilot probably never uses parafoveal vision to discover lights, an opinion he bases on the unlikelihood of achieving any high degree of dark adaptation (mentioning principally the need to look at lighted instruments) and the factors which tend to raise visual thresholds, such as inferior window quality and aircraft movement. These factors, plus the fact that detection is usually accomplished without the pilot's knowing where or when to look, leads to the comparatively high "practical" threshold, and supports Middleton's contention that sightings are almost always foveal. Without conclusive evidence, however, peripheral sightings should not be entirely rejected. Cockpit instrument panels can be designed and operated so that instruments can be read without serious loss of dark adaptation, and other factors suggest that at least occasionally the high sensitivity and

other characteristics of a good measure of dark adaptation may be effective.

Some experimental work suggests that above absolute threshold the apparent intensity (foveal) of a red signal light is <u>greater</u> than that of a white or green signal. <u>Middleton & Gottfried</u> (1957), for example, working at levels in the neighborhood of the "practical" threshold, found that red signals of equal photometric intensity appeared as much as twice as intense as white signals. Other experimental data indicates that the relative peripheral sensitivity to red light is appreciably higher for signals above absolute threshold than at the absolute threshold. A similar increase in red sensitivity is observed when the eye is adapted to a brighter background (Kinney, 1958). The results of these laboratory experiments are very difficult to apply to field situations, and serve mainly to underline the extraordinary complexity of the psychophysical phenomena involved. In the absence of definitive experiments which relate directly to visual collision avoidance, sweeping conclusions, such as avoiding the use of red signals because of the low sensitivity of the dark-adapted peripheral retina for red light, should be avoided.

In any event, when the color of the signal light must be identified, it is clear that higher thresholds apply, that foveal viewing is probable or required, and that there are no very large differences in threshold for the colors of ordinary three- or four-color systems (Middleton, 1958, p. 102).

<u>Flashing Lights</u>

The effective intensity of flashing lights has been studied extensively under a great variety of experimental conditions (Projector, 1957). The generally accepted method for computing the effective intensity of a signal flash observed at or near threshold is that proposed by Douglas (1957) (based on the classical investigation of Blondel and Rey, 1912):

$$I_e = \frac{\int_{t_1}^{t_2} I \, dt}{.2 + (t_2 - t_1)}$$

where

I_e = the effective intensity

I = the instantaneous intensity at any time, t, during the flash

t_1 and t_2 = times near the beginning and end of the flash, selected to maximize I_e

Analysis of this equation shows that the flashing of a light signal at intervals makes more efficient use of luminous energy in producing intensity (and therefore visibility) than distributing the same energy in a steady-burning light. The increase in utilization of energy is of course inversely proportional to the frequency of the flash, but such increase must be weighed against the increase of the duration of the dark interval between flashes, when no signal is visible at all. It is also evident that short flashes are more efficient in producing high effective intensity than long ones (for constant total flash energy), but that the benefit of reducing flash duration reaches a maximum when the flash duration is appreciably less than the constant in the denominator, 0.2 second. Thus durations less than about 1/20 second are almost equally effective (for equal flash energy), no matter how short they may be.

While the variation of effective intensity of flashing lights with such other variables as color and background luminance is often more complex than the variation of the apparent intensity of steady lights with these variables, relationships established for steady signals, subject to the above equation, may be used for roughly approximating flashing signal characteristics.

Efficiency

The efficiency with which electrical energy is converted to visible light signals is of great importance in designing and evaluating navigation light systems. On any aircraft, however large or high powered, the unnecessary consumption of power, or the addition of excess weight or unnecessary bulk, results in measurable reductions in over-all performance. On smaller aircraft such waste may be critical, and decisive in determining a design's feasibility. Since standardization of light systems for all aircraft is essential, it is evident that efficiency, always an important consideration, may dictate the choice among alternatives.

In the final engineering design of a system to meet specified performance requirements, one or another particular component may be called for to produce maximum efficiency. In general, however, there are no categorically superior components--for example, particular light sources--which can be selected in advance as components of choice for meeting all possible requirements.

The efficiency with which electrical energy is converted into luminous signals consists of two parts: the conversion of electrical energy to luminous energy, or the "conversion efficiency," and the conversion of the luminous energy to light

signals with the required intensity distribution, color and flash characteristic, or "signal efficiency."

Conversion efficiency. The efficiency of conversion of electrical to luminous energy varies over wide limits. White fluorescent lamps may have efficiencies as high as 75 lumens per watt (LPW), green fluorescent lamps may produce as much as 125 LPW. Conventional incandescent lamps have efficiencies in the neighborhood of 10-20 lumens per watt. But the efficiencies of all light sources are largely dependent on compromises with other design criteria, most particularly the design life of the source and the required maintenance characteristics (the manner in which light output changes during the life of the source). For example, short-life photoflood incandescent lamps emit well over 30 LPW.

The efficiency of auxiliary equipment necessary to operate the source may significantly reduce the over-all efficiency of the equipment. For example, the conversion efficiency of a conventional condenser-discharge light is of the order of 30 to 40 lumen-seconds per watt-second.[1] But the efficiency of the auxiliary equipment necessary to operate condenser-discharge lights may be of the order of less than 50%. Thus the over-all conversion efficiency of condenser-discharge lights is comparable to that of incandescent lamps (Mullis & Projector, 1958).

Signal efficiency--intensity distribution. Navigation lights are all required to have a distribution of intensity in space. Minimum intensities are specified in all directions. The design of equipment to produce distributions with sharp cutoffs in any direction is generally easier if the light source is small. Whenever the light emitted by a light source is controlled or redirected by lenses or mirrors or baffles, some degree of inefficiency, often substantial, is introduced. Light energy may be partially absorbed in the process of redirection; it may be scattered or redirected in undesired directions; and it may be impossible to redirect some of it as desired.

It is essential to analyze efficiency in terms of intensity distribution rather than intensity in any one direction. If high intensity is desired only narrowly in one direction, it is possible, by redirecting in the desired direction the light flux emitted by the source in other directions, to

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1 Energy units are used to evaluate flashing source efficiency rather than the rate-of-energy-emission units used for steady lights.

obtain enormously high intensities. Thus, for example, a 600-watt landing light consisting of a small incandescent filament source and a parabolic reflector produces a narrow beam with a maximum intensity of over half a million candles. The efficiency with which the light flux is directed into the desired beam, measured in beam lumens per watt, is considerably less than the conversion efficiency of the filament source itself, although the intensity of the latter, in the absence of a reflector, would be only of the order of 1000 candles.

Signal efficiency--color. When the color of the flux emitted by a light source must be changed by the use of filters, efficiency may be substantially reduced. These reductions are measurable in terms of the transmissions of the filters for the light emitted by the source. With incandescent sources, the transmission of red and green filters (to produce Aviation colors) is of the order of 20% to 25%. If, however, the light source is a condenser-discharge light, the transmission for green is about the same as for an incandescent source, but the red transmission is only about half as much, or even less, depending on the particular lamp. The transmission for a blue filter would be appreciably higher. Virtually no filtering at all would be required for bluish white, whereas the bluish-white filter required for an incandescent source might have a transmission of 25-50%. It is evident therefore that different light source-filter combinations designed to produce the same signal color may have radically different efficiencies.

In general, color coding implies reduction of efficiency, and this must be taken into account in over-all evaluation of a system.

Signal efficiency--flashing lights. The signal efficiency of a flashing light can be evaluated by extending the computation technique of Douglas for effective intensity (Projector, 1958a). This method takes into account not only the effect of flash duration and instantaneous intensity, but also the distribution of effective intensity, which, in determining the efficiency of a steady light, is analogous to intensity distribution. As with effective intensity, the shorter the duration of the flash for a given flash energy, the higher the efficiency. Below about 1/25 or 1/50 of a second there is little to be gained by further reduction in duration.

Thus condenser-discharge lights, with flash durations of the order of a millisecond or less, make maximum use of luminous energy, but any light source, emitting a flash of very short duration, can operate with an efficiency not significantly less. For example, if the flash duration is of the order of

1/25 second, the efficiency is about 80% of the efficiency of a condenser-discharge light with the same energy content. If, however, the duration is of the order of 1/5 second, the efficiency may be only half that attainable with a condenser-discharge light.

Incandescent lamps can be flashed electrically, by interrupting the current supply, or can be designed into fixtures which produce flashing signals by occultation, by rotation, or by oscillation of directed beams. Because of the thermal inertia of incandescent filaments, short duration, high-intensity flashes are difficult to obtain by electrical flashing. It takes time to heat the filaments to incandescence and to cool them off between flashes. Occultation with shutters also involves inertia, mechanical in this case, and may also reduce efficiency if the flux emitted by the source during the dark interval is not utilized. Rotating beams, and, to some extent, oscillating beams can readily be designed to emit flashes of very short duration and high signal efficiency approaching that of condenser-discharge lamps.

If flash-pattern coding consisting of dots and dashes is used, it is not possible to obtain the high signal efficiency of short-duration flashes, since the dashes must be of appreciable duration to be distinguished from the dots.

The relative signal efficiency of flashing lights as compared to steady lights can be calculated (Projector, 1959b), but to do this, the repetition rate of the flashing light must be taken into account. For repetition rates of about 60-80 flashes per minute, relatively short-duration flashing lights may have signal efficiencies five times as great as comparable steady lights.

Signal efficiency--extended sources. All light signals originate in real or apparent sources that have extent. However, if under given conditions of observation this extent subtends less than a certain visual angle, the observer sees it as a point source. This means that only the intensity of the signal determines its visibility. If, however, the visual angle of the source exceeds the maximum angle for point-source observation, then the visibility depends on the size and shape of the source and on its luminance. The relationship between source size and shape and luminance has been studied by a number of investigators (de Boer, 1951).

When the results of these investigations are expressed in terms of the illumination produced at an observer's eye, we have a direct measure of the relative signal efficiency of the sources of different sizes and shapes. Results show clearly that sources having extent are substantially less efficient in producing signal visibility than point sources.

When viewed against a moderately dark background, a circular source subtending a visual angle of one degree must emit five times as much flux as a source subtending one minute of angle for equal visibility. The maximum angle for effective point-source viewing is about a half minute to 5 minutes, depending on viewing conditions.

A special category of extended sources is linear sources, such as tubular fluorescent lamps or closely spaced rows of individual point sources, where the critical visual angle is exceeded in only one dimension. Losses in efficiency with such sources are not as great as with extended-area sources, but are of the same character.

Another special case is that of designs in which light sources illuminate aircraft surfaces, which then provide the visible signal. The efficiency of such arrangements is especially poor. They not only have the inherent inefficiency of extended-area sources but are subject to losses in reflection and to losses arising from the difficulty of directing all the light from the source onto the surfaces, and all of the light reflected from the surfaces, in desired directions only.

Thus, maintaining high signal efficiency in a navigation light system can be achieved only by using effective point sources in all system components.

Other Engineering Considerations

Detailed engineering design of navigation light systems requires consideration of a number of factors which differ among aircraft. For any aircraft, the usual aeronautical engineering objectives of minimum weight, high efficiency, reliability, safety, and low cost are applicable. Since a standard navigation light system suitable for all aircraft is essential, some of these considerations will be of greater importance for some installations than others. For small aircraft, minimum weight, high efficiency, and low cost may be much more decisive. For high-performance aircraft, finding suitable locations for lighting fixtures may be more difficult. Capability of withstanding high temperatures may be an important requirement for some installations but of little importance for others. It is difficult to deal with such problems generally, but a standard navigation light system will require full consideration of the special difficulties that may be encountered on particular classes of aircraft, and may even require that different, but compatible, systems be standard for different aircraft categories.

V. THE ATMOSPHERE, BACKSCATTER, AND VFR

In a perfectly clear atmosphere, the illumination, E, at the observer's eye, is related to the intensity, I, of a light source and the distance of observation, D, by the inverse square law:

$$E = \frac{I}{D^2}$$

The atmosphere is never perfectly clear--even theoretically pure air attenuates light to some extent--and in general, the inverse square law must be modified to take into account the effect of the atmosphere. The modified law is Allard's Law (Middleton, 1958, p. 137):

$$E = \frac{I}{D^2} t^D$$

where t is the transmissivity of the atmosphere, or the transmission per unit distance (same units that D is measured in)

General flight in controlled airspace under visual flight rules, at altitudes up to 14,000 feet, is permitted only under atmospheric conditions which would result in at least 3-mile flight visibility in the daytime.

Table 2 gives the designation, daylight visual range, and transmissivity for several atmospheric classifications from the International Visibility Code (U. S. Coast Guard, 1956).

The two components of a light signal's attenuation--that due to the inverse square law and that due to atmospheric effects--contribute quite differently to the resulting illuminance. This is illustrated in Fig. 3, a graph of the relation between illumination and distance for various transmissivities, as given by Allard's Law. The source intensity used as a basis for the curves in the figure is 100 candles, the minimum intensity required by the CAR for anti-collision lights in all directions within 5 degrees of horizontal. Anti-collision lights that meet the requirements are likely to have peak intensities in excess of the required minimum. To convert the values for illumination given in the graph to values appropriate to sources of any intensity, it is necessary only to multiply the given value of E by the ratio of the new value of intensity to 100 candles.

Curves for four values of transmissivity are plotted. The upper curve, for a value of t = 1, represents the inverse square law without any atmospheric attenuation. The next

Table 2

Visual Properties of the Atmosphere;

International Visibility Code

Atmospheric Designation	Daylight Visual Range, Miles	Transmissivity (transmission/mile)
Exceptionally clear	over 31	over .88
Very clear	12 to 31	.73 to .88
Clear	6.2 to 12	.53 to .73
Light haze	2.5 to 6.2	.21 to .53
Haze	1.2 to 2.5	.044 to .21

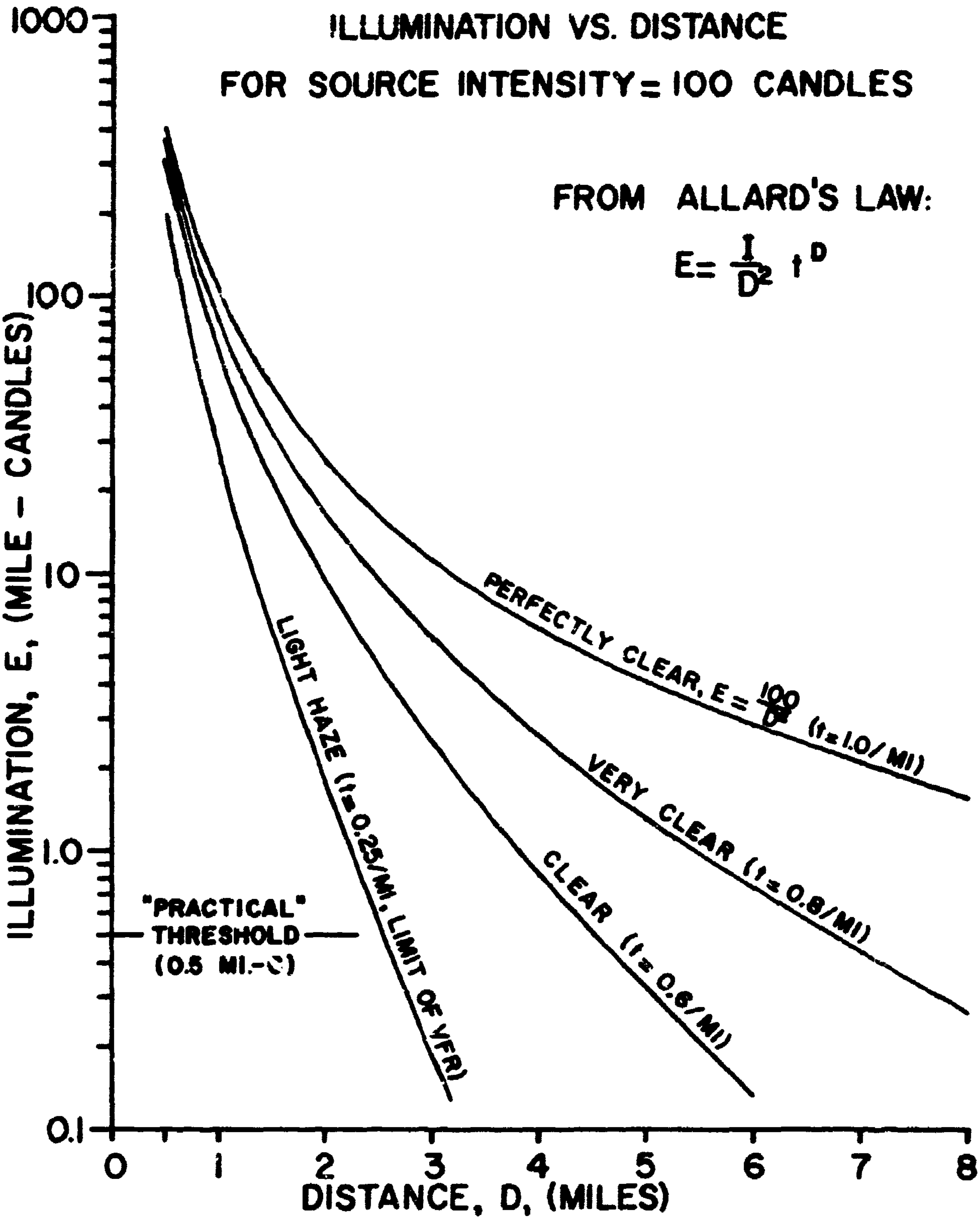

Fig. 3. Illumination from a 100-candle signal at various distances for selected values of atmosphere transmissivity.

curve, for t = 0.8/mile, represents a "very clear" atmosphere. The third curve, for t = 0.6/mile, represents a "clear" atmosphere. The fourth curve is very important: the value for t, 0.25/mile, represents an atmospheric condition when the daytime visibility is about 3 miles, the minimum flight visibility for VFR operation in control zones, control areas, and transition areas.

The "practical" threshold of illumination, 0.5 mile-candle, is indicated on the graph.

It is evident from the figure that at closer ranges in clear atmospheres the principle source of reduction in illumination with distance is the inverse square law. At longer ranges and at lower atmospheric transmissivities atmospheric attenuation is increasingly important. Atmospheres representing the limits of VFR are decisive in limiting visibility at longer ranges.

The figure shows that for marginal atmospheres, when t = 0.25/mile, the illumination is below the "practical" threshold at 3 miles (the threshold range is 2-1/2 miles). Since the "practical" threshold is, as noted, a very rough approximation, and since actual anti-collision light intensities exceed requirements to some extent, it may be judged that anti-collision lights currently in use do provide approximately the visual ranges required.

If however an aircraft does not have an anti-collision light, and has only the presently required position lights, the visual ranges may be seriously submarginal. The CAR, for example, specify a minimum intensity of only 5 candles for the wingtip lights in directions from 20 to 110 degrees outboard--1/20 the intensity for which the curves in the figure were computed. Applying this ratio to the illumination scale in the figure, it can be seen that when the intensity is 5 candles the "practical" threshold illumination will be attained at 3 miles only if the atmosphere is "perfectly clear;" any atmosphere denser than "clear" will produce distinctly sub-marginal illuminations. On the other hand, increasing intensity from 100 to 1000 candles will increase the threshold range from 2-1/2 to about 4 miles for the marginal atmosphere, or from 4-1/2 to about 7 miles for a "clear" atmosphere with a transmissivity of 0.6/mile.

By increasing intensity, increased range can be obtained for any atmospheric condition; but in the marginal condition, atmospheric attenuation becomes so overwhelming that the gain in visual range becomes less and less as intensity is increased. Figure 4 illustrates this effect.

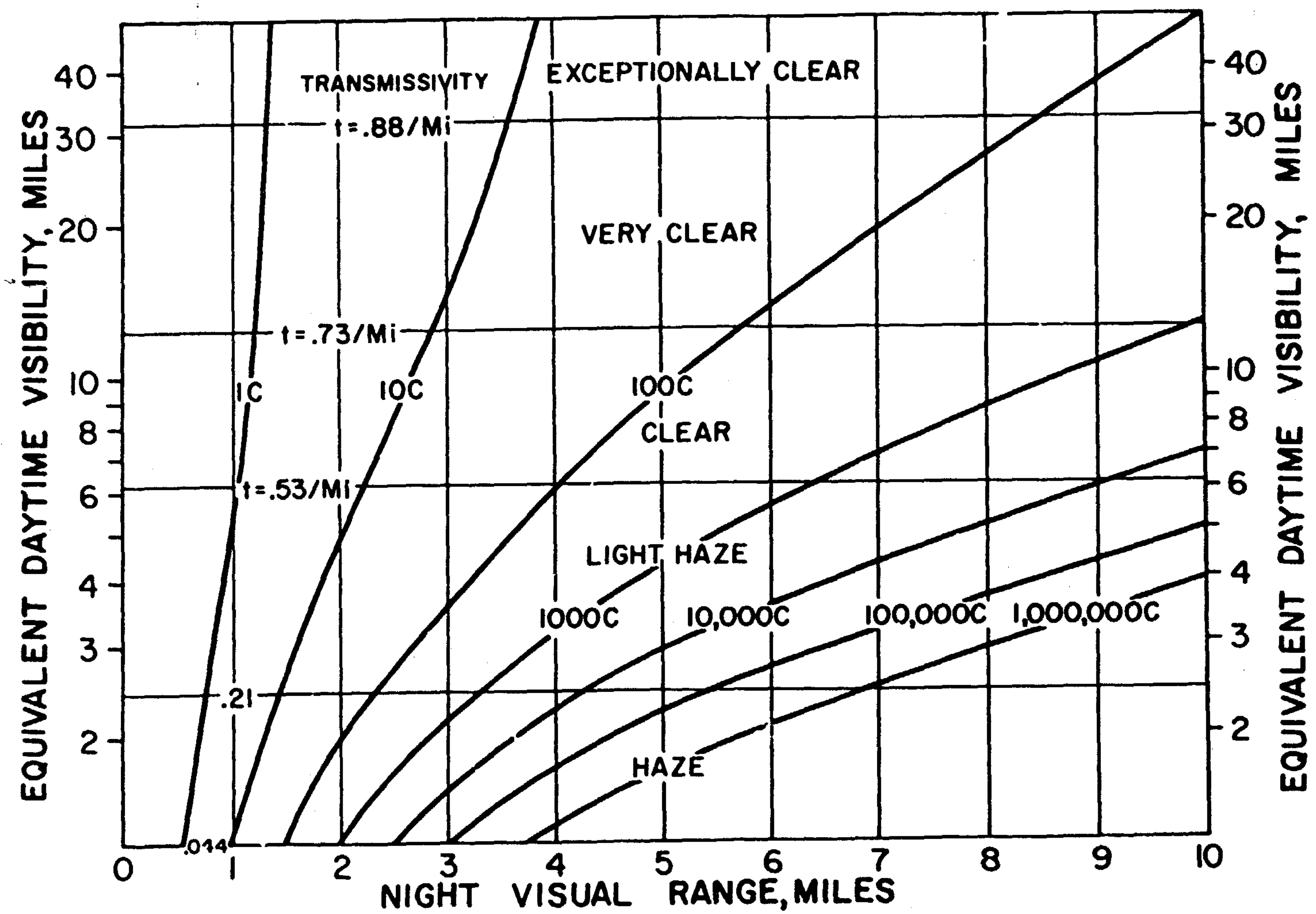

Fig. 4. Night visual range of lights of various intensities as related to atmospheric condition. The atmospheric condition is given in terms of the daytime "meteorological range" for objects in an equivalent atmosphere. Descriptive categories for the atmosphere, according to the International Visibility Code, as well as transmissivities at the boundaries between these categories are shown. The night visual ranges are based on the "practical" threshold of 0.5 mile-candle.

Another possible approach to increasing visual range is to restrict VFR to narrower ranges of atmospheric conditions. It may be seen in the figure, for example, that if VFR flight were limited to "clear" or better atmospheres, with a daytime visibility of at least 6 miles, then the marginal visual range for a 100-candle signal would increase from about 2-1/2 to 4 miles, the same increase that was obtained by increasing the intensity from 100 to 1000 candles for an atmosphere with 3-mile visibility. Or, for a signal of 1000 candles, the range would be increased from about 4 to over 6-1/2 miles. If light intensity is increased to 1000 candles and VFR restricted to "clear" or better weather, then the increase of range under marginal conditions would be from 2-1/2 miles to over 6-1/2 miles.

Signal Color and the Atmosphere

Under certain conditions the atmosphere may strongly affect the color of observed lights. The yellow or red of the sun when on the horizon or when observed through dust or smoke is a familiar phenomenon. Within the range of conditions of interest in navigation light systems, however, selective attenuation effects of the atmosphere are seldom of sufficient magnitude to produce such striking effects.

The selective characteristics of atmospheric attenuation are very complex and in many respects not well understood (Middleton, 1958). It is possible to describe some of these characteristics in a general way to indicate their applicability to navigation lights.[1]

As noted earlier (see Fig. 3) reduction in signal illumination with distance consists of two parts, that due to the inverse square law, and that due to atmospheric attenuation The inverse square law is nonselective; all colors follow precisely the same decay curve.

The contribution of atmospheric attenuation to reduced illumination is the difference between the illumination at a given distance as computed by the inverse square law and the actual illumination at that distance with a particular atmosphere. Thus, referring to Fig. 3, the total atmospheric transmission at 5 miles, when the transmissivity is 0.8/mile, is $1.3 \div 4 = 0.325$. When the transmissivity is 0.6/mile, the

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[1] It should be emphasized that this discussion is limited to the appearance of observed signal lights at night. The effect of the atmosphere on the observed colors of objects in the daytime is substantial (Applied Psychology Corporation, 1961b). The effect of color on backscatter will be discussed later.

total transmission at 5 miles is 0.3 + 4 = .075. For shorter distances (or clearer atmospheres) transmission is appreciably higher. At longer distances it falls rapidly.

Selectivity in atmospheric transmissivity can affect the appearance of observed signals of different colors in two ways: (a) the apparent intensities of the different colors can decay differently with distance, so that two signals that appear equal in intensity when observed at short ranges can appear unequal at long ranges, and (b) the observed color of the signals can change with distance.

Atmospheric selectivity has been studied by a number of investigators, often with surprisingly different results. Sometimes no selectivity has been found at all, at other times the shorter wave lengths (blues and greens) have been found to have higher transmissivities than the longer wave lengths (reds and yellows). Most often, however, and particularly for the kinds of atmospheres of greatest interest in VFR flight, the longer wave lengths have been found to have higher transmissivities than shorter ones (Middleton, 1958).

Those experimental results considered by Middleton to be most representative of the atmospheric conditions important in flight are presented in Table 3 in a form indicating the magnitude of the effects as related to operational situations. The data for red and green were obtained with lamps and filters of the general type that might be used to produce these colors in navigation lights.

It is evident from the table that the effect of selectivity on apparent intensity is not very large. The largest difference in the table is in the ratio 2:1 approximately, occurring at 10 miles for green transmissivities .60 and .53/mile, and at 5 miles for green transmissivity .25/mile. But comparison with Fig. 4 shows that all three conditions would produce signals well below the practical threshold even for a 1000-candle signal. The next largest difference is about 1-1/2:1 at distances and transmissivities above threshold for a 1000-candle signal but below threshold for a 100-candle signal; differences in illumination of such magnitude are not considered very important. Most of the other differences are considerably smaller than 1-1/2:1. In sum, atmospheric selectivity may be considered to have only a minor effect on the apparent relative intensities of red and green signals.[1]

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[1] White signals and yellow signals are intermediately affected, so that the difference between red and green is the maximum to be found in navigation light systems. Blue signals are attenuated differently, about as much more than green as red is less, but blue signals are not useful for long-range signaling and are not considered here (Middleton, 1958, p. 173).

Table 3

Atmospheric Selectivity

(Total Transmission at 3, 5, and 10 Miles for Various Transmissivities)

Atmosphere Description (Based on Green Transmissivity)	Transmissivity (Per Mile)		Total Transmission					
			3 Miles		5 Miles		10 Miles	
	Green	Red	Green	Red	Green	Red	Green	Red
Exceptionally Clear	.90	.93	.73	.79	.59	.68	.35	.46
Very Clear	.80	.83	.51	.57	.33	.40	.108	.155
Clear	.60	.64	.22	.27	.078	.110	.006	.0115
Boundary, Clear and Light Haze	.53	.57	.149	.184	.04	.06	.0018	.0035
Light Haze (Limit of VFR, 3-mile visibility)	.25	.29	.016	.024	.001	.002		

The effect of atmospheric selectivity on the apparent color of signals depends not only on the magnitude of selectivity itself but also on the particular color. In general, longer wave lengths are less attenuated than shorter ones, and the apparent shift of all colors is toward the red end of the spectrum. Red itself is not noticeably affected, however, since all the wave lengths that compose red signals (of the kind used in navigation lights) are within a comparatively narrow band. Green signals generally consist of a broader spectrum of wave lengths from blue to yellow. Selective attenuation may make the color somewhat more yellow. However, with most broad-spectrum greens the magnitude of the strong components of the color in the green region of the spectrum is much larger than that of the blue or yellow components, so that even in the more selective situations the total shift of color is relatively small. In the use of white signals, however,there are substantial components throughout the spectrum. White signals therefore may be noticeably yellowed if observed when the selectivity is high. Even in such cases, the shift would rarely result in a confusion with red signals. However, if distinction from yellow signals is required, it may be necessary to consider the possibility of confusion.

If the limits of VFR are changed to the boundary between light haze and clear, the maximum color shift at any given distance will be reduced. The green-red ratio of transmission increases with atmospheric density for a given range, as may be noted in Table 3. Significant color shifts would thus be limited to very long ranges. If color identification errors occur at these ranges, they are less likely to lead to trouble and would in any event be readily corrected as a sighted aircraft closes in and the range is reduced.

At or near threshold, color identification is more difficult than at higher levels, the degree of difficulty varying with the color (Stiles, Bennett & Green, 1937; Rautian & Speranskaia, 1955). The "practical" threshold, 0.5 mile-candle, is close to the color identification threshood, but most observers suggest that somewhat higher thresholds, of the order of 2 mile-candles, are preferable if a high order of certainty of identification is required (Stiles, et al, 1937; Rautian & Speranskaia, 1955; Hill, 1947).

Backscatter

The attenuation of light signals transmitted through the atmosphere results from absorption and scattering (due to reflection, refraction, and diffraction). In "aerosols" (atmospheres consisting essentially of air and water vapor) absorption of light is very small compared to scattering, and can usually be neglected (Middleton, 1958). It is only

in atmospheres containing large amounts of industrial smokes or dust that absorption may be significant.

Light is scattered by the aerosol in all directions. That scattered at and near 180 degrees (the direction back to the light source) constitutes the "backscatter," and is of special importance. When backscatter is very large, as in the case of fog or clouds, it can be so disturbing that a pilot must turn off his navigation lights to avoid serious impairment of his vision. However, such gross effects occur when the atmospheric condition is well outside VFR limits. However, the disturbing effects of backscatter may be significantly large even within the limited range of VFR atmospheres, and may impose important design requirements on navigation-light systems.

The deleterious effects of backscatter may include (a) direct reduction of light-signal visibility by increase of the background luminance against which the signals are seen, (b) indirect reduction of signal visibility by loss of dark adaptation, and (c) more or less severe distracting or disorienting effects on a pilot, especially if the light-source flashes. (In this connection it may be noted that backscatter from flashing signals originating in rotating beacons may have different effects from that originating in electrically flashed lights.)

Visual range (or transmissivity) and backscatter are closely related (Curcio & Knestrick, 1958). There is very little backscatter in the clearest atmospheres, but backscatter can reach serious levels near the limits of VFR. Curcio and Knestrick found a relation between meteorological range, V, and the intensity, S, of backscatter:

$$V = \frac{C}{S^{1.5}}$$

where C is a constant.

To the extent that transmissivity is selective, so also is backscatter. As noted earlier, selectivity varies with the attenuating components that make up any given atmosphere. For aerosols in the range of interest in VFR, selective transmissivities are shown in Table 3, indicating a higher transmission for red than for green. The corresponding backscatter will be <u>less</u> for red than for green. While the effects of selectivity are generally not large, they suggest that red signals are preferable to shorter wave-length signals, both because of higher transmissivity and because of lower backscatter.

A more important effect, favoring the use of red signals where backscatter is a problem, arises from the spectral sensitivity distribution of the different parts of the retina. The central part of the eye is much more sensitive to red light than is the periphery. Thus when the eye is more or less dark adapted, it is much less likely that red signal sightings will occur in the periphery. By the same token, however, red backscattered light will be far less noticeable in the periphery than will light of other colors. Since the fovea is relatively small, subtending approximately 5 degrees of visual angle, and the periphery very much larger, the apparent difference between red backscatter and backscatter from other colors is often strikingly large, even though the ability to detect signals in the fovea is not greatly affected. Knoll et al (1946) have shown that the visibility of a point source is affected only by its adjacent background, within about 0.4 degree.

The intensity of backscattered light is proportional to the intensity of the signal light that causes it. Thus as the intensity of navigation lights increases, backscatter becomes more important and may on occasion decisively affect the design of a light. The problems of backscatter arise primarily in connection with light projected forward into the pilot's field of view; backscatter from rear projecting lights is important only when a pilot searches to the side or rear.

A series of tests of the ability of observers to detect target lights through backscatter and to identify color is described in Applied Psychology Corporation Technical Reports Nos. 6, 9, and 14 (1962a). These tests were carried out at a field visibility test range, and all test conditions were carefully controlled with the exception of the properties of the atmosphere, whose transmissivity was measured. Red, green, and white target and backscatter lights were used, the backscatter light was operated both steady and flashing, and both foveal and peripheral sighting were tried.

Surprisingly, the results were largely negative. The condition of the backscatter light--its color, or whether it flashed or burned steadily--had little or no effect on the ability of pilots to detect the targets or to identify their color. These negative results were obtained with a backscatter light of relatively high intensity (about 5500 candles), and in much of the test the atmosphere was close to the limiting VFR atmosphere corresponding to a daylight visibility of 3 miles.

The significant differences that did appear in the data were generally attributable to atmosphere attenuation and to selectivity in the attenuation, and to the difference in eye

sensitivity for different target colors peripherally and foveally.

It thus appears that backscatter in the amounts likely to occur with navigation light systems, even if they include components of appreciably higher intensities than are now used, will not significantly affect the detectability or identifiability of intruder lights.

There are, however, other possible effects of backscatter which may be important. These include, as noted previously, distracting or disorienting effects. Pilots have noticed and reported strong disturbing effects. These reports suggest that there are significant differences between flashing and steady backscatter, and between backscatter of different colors. Investigation of the psychological effects of backscatter will be increasingly important as high-intensity navigation lights come into use.

It is therefore useful at the present time to design navigation light systems that minimize backscatter as much as possible, even though some of its expected deleterious effects have not been confirmed by tests. Backscatter effects on a pilot can be minimized in a number of ways:

1. By lateral separation of the light source from the pilot. Thus, wingtips constitute the most favorable location for forward-projecting lights.

2. By longitudinal separation of the light source from the pilot. This does not result in as great a reduction in backscatter as does lateral separation, but the divergence of light beams results in a marked reduction in luminous flux density (and with it the brightness of backscatter) with distance from the source, particularly very near the source. It is thus advantageous to locate a fuselage-mounted light (an anti-collision light for example) as far back from the cockpit as practicable.

3. By intensity distributions with sharp cutoffs inboard (this should be coupled with lateral separation). This results in very low backscatter brightness in the areas directly forward of the cockpit, but permits high signal intensity forward for the benefit of the pilot of an intruder aircraft.

4. By limiting high-intensity forward-projected light signals to red, for reasons described above.

VI. LIGHTS IN THE DAYTIME

In Chapter IV it was indicated that the threshold illumination of a light signal is affected by the luminance of the background against which it is seen. As the luminance of the background increases, the threshold illumination increases. For dark backgrounds up to the range of moonless starlit night skies, the increase in threshold signal illumination is not large and does not significantly affect the "practical" threshold. As sky luminance increases above that of the moonless sky, the threshold illumination rises rapidly. In a bright moonlit sky, the threshold is about 100 times greater than in a dark sky. In the daytime, thresholds are 1000 to 10,000 times higher (Blackwell, 1946; Knoll et al., 1946; Jainski, 1960).

Thus, extremely high intensities would be required to provide adequate signal visibilities throughout daylight conditions. The intensity required to provide a visual range of 3 miles when the meteorological range is 3 miles and the background luminance is 1000 footlamberts is about 250,000 candles. Even this intensity is not enough, however. While 1000 footlamberts is fairly representative of clear blue sky luminance, the luminances of particular portions of the sky often attain much higher values. For example, Hopkinson(1954) measured values as high as 8000 footlamberts near the sun. The sun itself has a maximum luminance about half-a-billion footlamberts. The extreme difficulty of looking into the sun, or even near it, makes it generally impracticable to attempt sighting in these directions By using dark glasses, especially when the sun's disc itself can be obstructed (for example, by aligning it with a part of the aircraft structure) it is sometimes possible to search in the neighborhood of the sun. Even so, it is far beyond practicability with the aid of lights.

Intensities of 250,000 candles can be produced in lighting equipment, but only in limited directions and with considerably higher expenditures of power (and increased weight and bulk) than are likely to be considered feasible, even for very large aircraft. Six-hundred-watt landing lights, for example, have peak intensities of about 600,000 candles, but their beam widths, measured at the points of 10% of peak intensity, are only about 11x12 degrees. Complete coverage with a reasonable distribution of such high intensities in all directions would require many thousands of watts and considerable bulk and weight and would present many other engineering problems such as high temperatures, reduced aerodynamic performance resulting from necessary projections, etc.

It is clear then that lights cannot be expected to provide a complete system for daytime visual effectiveness. Nevertheless, daylight includes visual conditions not sharply separated from night. It is therefore appropriate to inquire how far into daylight conditions and under what particular conditions lights may be useful.

According to the CAR, navigation lights are to be turned on between the hours of sunset and sunrise. The luminance of the sky near the horizon at sunset or sunrise on clear days is as low as 100 footlamberts. (Koomen, Lock, Parker, Scolnick, Tousey, & Hulburt, 1952) If clouds are present, much lower luminances may occur. Furthermore, the backgrounds against which aircraft may be sighted may be dark clouds or dark terrain rather than clear sky. The data of Knoll et al. (1946) suggest that at a background luminance of 100 footlamberts threshold signal illumination will be 100 to 1000 times the threshold on a starlit night. If this is compared with Fig. 3 of the last chapter, it is evident that with intensities of 100 candles, raising the threshold by a factor of 100 will result in sighting distances against 100 footlambert backgrounds of well under 2 miles.

It is evident that navigation lights conforming to present requirements (minimum of 100 candles in the horizontal plane for anti-collision lights) give substantially less than 3-mile visibility under many marginal conditions in twilight. Aircraft without anti-collision lights, having only conventional position lights, are required to present only 5 candles of intensity from 20 to 110 degrees outboard on each side of the aircraft. Against a dark background, a signal with an intensity of 5 candles would have a "practical" visual range of about 3 miles in a "perfectly clear" atmosphere, but in an atmosphere with 3-mile visibility, the range would be only about 1-1/3 miles. Against a background with a luminance of 100 footlamberts, such a signal would have a negligible visual range.

With lights that barely meet the present minimum requirements, there is some question whether their intensities are adequate even to cover the hours from sunset to sunrise. On the other hand, backgrounds at sunset or sunrise may have luminances appreciably less than 100 footlamberts, the value on which the above discussion is based. It may therefore be reasonable to turn navigation lights on before sunset (or keep them on after sunrise) to take advantage of the possibility, however small, that some conspicuity may be gained.

It is of value to compare the daytime visibility of the aircraft with the visibility of the light signal itself. Because of the many variables in each situation, this comparison

is complex. As indicated earlier, light signals can be visible in the daytime if their intensity can be made very high. But only large aircraft could conceivably provide power for sufficiently high intensities, and the large aircraft are already more visible because of their size.

Howell (1958) investigated the visual range of high intensity lights in the daytime and of the aircraft carrying the lights. Three sizes of lights were used, each mounted in an oscillating fixture so that the signal was a flashing white light. The lamp power consumptions were 250, 600, and 900 watts. The effective intensities of these signals are estimated to be (very approximately) 15,000, 50,000, and 200,000 candles, respectively.[1]

The 250-watt unit with an estimated effective intensity of 15,000 candles was seen appreciably less far than the aircraft itself (a DC-3); the aircraft threshold averaged 17.1 miles and the signal light threshold 8.3 miles.

The 600-watt unit with an estimated effective intensity of 50,000 candles was seen on the average about as far as the aircraft itself. The 900-watt unit with an effective intensity of 200,000 candles was seen farther away than the aircraft in each of four runs.[2]

Data such as the above suggest that little is to be gained from daytime use of lights of practicable intensities. If the data are examined in detail, however, the suggestion that lights can be of <u>occasional</u> value in the daytime appears to have more merit. The extreme variability of daytime visibility of the aircraft is poor. If this should occur when the background is dark, lights may be helpful.

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1 Static data were given in the report for the intensity distributions of the lights used, but insufficient data about the oscillatory mechanism to determine the time-intensity distribution. Furthermore, there is considerable uncertainty in the value of the constant, a, in the Blondel-Rey equation, for effective intensity computations appropriate to daylight viewing. The estimates of the effective intensities are therefore very crude and indicate only the order of magnitude.

2 The sighting distances in this series of tests (from 10 to 20 miles) were well in excess of those obtained under normal operational conditions. Howell (1957) found that sighting distances in operational situations are 3 times shorter than those for observers who knew where and when to look and were not distracted by other duties. Marshall and Fisher (1959) found a similar ratio of sighting ranges for a small aircraft in a terminal area but at very much shorter distances and with a number of completely missed detections.

A contrast of an aircraft target against a background may be positive, negative, or a mixture of both. The contrast of a light against a background is always positive.

A high negative contrast, as occurs, for example, with a backlighted aircraft seen against a background of bright sky, is probably the commonest mode of seeing aircraft targets. A light signal, unless it is overwhelmingly intense, cannot improve the conspicuity of such an aircraft. (On rare occasions, it may even noticeably decrease if by effecting an apparent increase in the luminance of the target aircraft.) If, however, the background is dark and the contrast is positive or small, lights of moderately high intensity may improve conspicuity.

Under a heavy overcast, sky luminances as low as 13 footlamberts have been found just before sunset (Hopkinson, 1954). Middleton (1958) has summarized the available data on the luminance of the sky near the horizon at sunset on an overcast day and found it to average about 3 footlamberts. Dark clouds and some terrestrial backgrounds may often have luminances in midday of 100 footlamberts or less, and terrestrial backgrounds near sunrise and sunset may be very dark.

Thus, while lights with the intensities available today are of little value in the daytime, their occasional usefulness under marginal conditions suggests that they be turned on well before sunset, kept on until well after sunrise, and turned on on all other occasions when there is a possibility that they may serve a useful function. As higher-intensity lights become available, usefulness will extend further into marginal daylight conditions, and rules governing their use should be correspondingly changed.

The above discussion is based on the probable sighting range of lights in daytime or in marginal lighting conditions. In addition to providing detectability, navigation light systems serve the function of giving sector-coded aspect information, which is of value within sighting ranges. For example, in the vicinity of airports, traffic must be kept in sight and tracked at separation distances often less than one mile. In such cases navigation lights may be helpful and should be used well into marginal daylight conditions.

It is conceivable that the most effective lights for daytime use may be different from those used at night. Backscatter, for example, which dictates the use of red as the color of anti-collision lights, is not a daytime problem. It may be desirable therefore to use a white anti-collision light in the daytime with five times the intensity of presently

used red anti-collision lights. On the other hand, since present lights extend so little into marginal daylight and are therefore almost exclusively night lights, it may be preferable to avoid nonstandard lights and use the same system in the daytime as at night.

VII. LIGHTS AND BACKGROUNDS

It was shown in Chapter IV that the threshold illumination of a signal light increases as the luminance of the background against which it is seen is increased. When the background itself consists of numbers of small lights, such as the lights of a city or a starlit sky, an element of confusion enters, and an otherwise visible signal may be undetected. Against a starlit sky, where all the background lights are of a single character, most aircraft signals are fairly distinctive, especially if they appear more intense than the stars, and can be distinguished by their color or flashing characteristic as aircraft lights. City lights and ground or tower obstruction marker lights may be extremely diverse in color, intensity, flashing characteristic, etc., and may be easily confused with aircraft lights. If ground lights emit signals similar in character to aircraft lights (as is the case for example, with red flashing ground obstruction markers and red flashing anti-collision lights), identification is possible only by using secondary visual cues such as relative movement.

Under cruising conditions, at intermediate and high altitudes, it seldom happens that the confusion of aircraft lights with ground lights is serious. If the intruder aircraft is near enough to one's own altitude to constitute a possible collision threat, ground lights in the background are likely to be far away and faint. At low altitudes, however, especially in densely populated areas and terminal areas, the difficulty of distinguishing aircraft lights may be very great.[1]

In terminal areas, a pilot may be confronted not only with the general difficulty of distinguishing aircraft lights from ground lights, but he may have to do this for several aircraft at the same time. Once a light has been detected, any motion against the background of ground lights will distinguish it as an aircraft light. But under certain relative speed conditions there may be no motion against the background, or the motion may be very small.

The general subject of the distinctiveness of lights against backgrounds of other lights has been investigated,

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1 This difficulty is unnecessarily compounded by lack of standardization. If the number of different signals that are found on aircraft can be reduced, it will be easier for a pilot to identify many lights as ground lights.

but not in the context of aircraft operations. The results are of interest here, but definitive experiments that include the important operational factors are yet to be undertaken.

Langmuir and Westendorp (1931) investigated the conspicuity of a flashing light against backgrounds of numbers of steady lights. They found that if the target light was well separated from them (3 degrees), the background lights had little effect on target visibility, even when the background lights were hundreds of times more intense than the target. However, when the target light was close to any of the background lights (0.75 degree) then intense background lights multiplied detection time by as much as five times.

In two experiments by Crawford (1959, 1960), the effect of steady and flashing background lights on the detectability of a steady or a flashing target light was studied. The target light was always yellow and the background lights red and green. It was found that the most conspicuous target was a flashing light against a background of steady lights, and the least conspicuous a flashing light against a background of flashing lights. When various mixtures of steady and flashing lights were used as background the advantage of a flashing light over a steady light was lost when only a very few of the background lights flashed.

The experiments described above were done in static conditions. An experiment carried out under more realistic conditions is reported in Applied Psychology Corporation Technical Report No. 13 (1962e). The backgrounds were actual city lights as seen from a nearby mountain. While there was no relative motion (the observers and the target lights were stationary during the observations), the dynamic character of the lights in the background (moving vehicles, flashing signs, etc.) was a factor in the test design. Twelve distinctive parts of the background were used, ranging from rural unlighted areas to intensely lighted commercial sections. Red, green, and white signals were used, and they were flashed either regularly or in a dot-dash code. As measured by the time it took to discover them the red signals were found to be more conspicuous than white. Green signals were intermediate between white and red. No difference was found between the two modes of flashing the signals.

While experiments such as the above are suggestive they cannot be considered conclusive. The work of Crawford suggests that there are not likely to be general conclusions valid for all signals against all backgrounds.

It is possible, however, to present some tentative generalizations.

1. Increased intensity will help distinguish aircraft lights from backgrounds.

2. Flashing aircraft lights will provide good conspicuity except against backgrounds that have a number of flashing lights, especially when they have characteristics similar to the signal.

3. The regularity of the flash of aircraft lights, whether pattern coded or not, probably helps distinguish them from background lights that flash erratically or that flash in regular but markedly different ways.

4. Pattern coding of flashing lights probably does not add to conspicuity, but should help resolve ambiguity. For example, an anti-collision light coded with a dot-dash altitude code can be distinguished readily from a regularly flashing uncoded tower obstruction light.

5. The most reliable factor that will help identify an aircraft light is relative motion against the background. This motion should also help make the light more conspicuous.

VIII. SEARCH TECHNIQUES AND COCKPIT VISIBILITY

Most collisions occur at times when atmospheric conditions are favorable for visual sighting of aircraft, but, for one reason or another, the colliding aircraft is not detected at all or is detected much too late. Methods for increasing the conspicuity of aircraft lights have been discussed elsewhere in this report, but many factors within the observing pilot's cockpit profoundly affect the likelihood of detection of a target. These include the pilot's search habits and technique, and the physical arrangements of the cockpit itself: the visibility afforded by the windows, the quality of the glazing, and the visual environment.

Many of these factors are much the same at night and during the daytime.[1] The quality of the glazing, for example, similarly affects both day and night visibility. Inadequate window area or structural obstructions in the field of view limit visibility in the same way both day and night. In some respects, however, visual processes differ materially, and this difference has a bearing on search habits and effectiveness.

It has long been recognized that visibility from the cockpits of modern aircraft is severely restricted, so much so that for some collision approaches the pilots of both aircraft are unable to see the other, regardless of conspicuity (Edwards and Howell, 1956; Fisher and Howell, 1957; Calvert, 1958; Zeller and Burke, 1958; Wulfeck et al., 1958). Conflicting demands make it impossible to provide sufficient cockpit visibility to meet the requirements of visual collision avoidance. It should nevertheless be possible to provide better visibility than now exists and particularly to eliminate "double blind" approaches.

In general, there are no "safe" directions of approaches, although under present conditions it is too much to expect a pilot being overtaken to detect and be responsible for detecting the overtaking aircraft. Nevertheless, responsibility should be placed on both pilots, requiring that present visibility limits be expanded not only in the horizontal plane but vertically as well.

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1 A discussion of some aspects of daytime search is contained in Applied Psychology Corporation Final Report No. 1, The Role of Paint in Mid-Air Collision Prevention (1961b).

Pilots are expected, when flying VFR, to see and avoid other aricraft. But they are required to spend much of their time on other visual tasks. On long flights they are subject to fatigue, which lowers their visual alertness. Furthermore, a pilot's attention is limited to a single direction at a time, and complete, effective coverage of the field of view must take time. In the daytime maximum visual effectiveness is limited to a small region in the center of the visual field--so much so that most detections are believed to occur when the eyes are directed narrowly toward the intruder. (Lamar, 1960; Middleton, 1958).

The properties of the eye at night can differ radically from the properties during the daytime, affecting both the effectiveness of search and the kind of search technique that should be used. Visual capability in the periphery of the light-adapted eye is very poor compared to that of the fovea (hence the likelihood that daytime detection will take place in the center of the eye). When the eye is dark adapted, however, sensitivity of the periphery to a light signal is much higher than that of the fovea, except for red light. It is thus possible, if dark adaptation can be achieved, that search can be effective through the much larger peripheral visual field and detection can be made without target fixation. In this case, much less scanning would be required for adequate coverage, and it would be much less likely that targets would be missed (Mertens, 1956).

Unfortunately, complete dark adaptation is seldom possible. Light, both inside and outside the cockpit, precludes this in general. Middleton has stated the ambient light insude the cockpit is likely to be so unconducive to dark adaptation that it is likely that sightings are actually made foveally at night as well as in the daytime. The so-called "practical" threshold of signal illumination (see Chapter IV) is well above the actual limits of visual sensitivity, suggesting that the high sensitivity of the fully dark-adapted eye is not exploited in operational situations.

Dark adaptation is a matter of degree. Between complete dark adaptation and full light adaptation there is a continuum of intermediate states. In this range, near the dark end, there are sensitivity advantages to be gained even though they are not of the large magnitude characterizing complete dark adaptation. By judicious control of the ambient light in the cockpit (the instrument lights, light from the cabin, etc.) pilots can often achieve and maintain a fair degree of dark adaptation, which can maximize sensitivity generally, and may occasionally result in peripheral sightings that might otherwise be missed.

Scanning usually consists of a series of eye movements, preferably covering the field of view systematically. If the target light is flashing, and no considerable dark adaptation has been achieved, then detection is likely to occur if the flash takes place while the eyes are fixated in the neighborhood of the target. If the flash occurs when the eyes are moving, it is less likely to be seen than if the eyes are stationary. Measures of the effective intensity of flashing lights are based on steadily fixated eyes; it is presumed that the energy from the flash is used to form an image at a single point on the retina. If because of eye movement the image is spread along a line on the retina, the energy density at any point is very much reduced and the signal correspondingly less visible. If, however, the duration of the flash is extremely short, the image may be completely formed in a single retinal location even though the eye is moving, and the target's visibility might not be reduced. Mackworth and Kaplan (1962) found just such an effect with a target illuminated by a condenser discharge light having a flash duration of about one microsecond.

Flash durations as short as one microsecond cannot be obtained in navigation light systems, even with condenser-discharge light sources, but it is worthwhile to investigate the possibility that during operational search very fast flashes of practicable durations may provide greater conspicuity than slower flashes.

The serious limitations on cockpit visibility suggest that it may be worthwhile to consider the use of rear-view mirrors or optical scanning devices in order to provide search capability in otherwise blind directions (Howell, 1958; Fisher, 1957). Optical aids of this type have not been found fully satisfactory, but even limited capability would be of value, particularly when a pilot desires to assure himself that the air is clear in the direction toward which he wishes to maneuver (Applied Psychology Corporation, 1962g).

IX. RULES-OF-THE-ROAD

Although regulations covering IFR and VFR flight altitudes offer a measure of protection against air collision, there are many situations in which two aircraft encounter each other at the same altitude, usually when one or both are climbing, descending, or turning, or when two VFR aircraft are on headings within the same east or west half of the compass. In the latter case their paths may be intersecting at any angle from nearly head-on to parallel.

If a pilot is confident that there is no danger of collision with a sighted aircraft, he need do nothing other than reaffirm occasionally that his judgment is still correct. The occasions when a pilot must consider that a collision possibility cannot be ruled out may be grouped in two classes:

1. Those in which the fixity of bearing is or might be a major source of information;

2. Those in which the fixity-of-bearing criterion is not applicable because one's own aircraft is maneuvering or the intruder is known or presumed to be maneuvering.

The second class of situations characterizes terminal areas, and at busy airports may involve several intruder aircraft at once. In such cases the pilot must anticipate aircraft movements and attempt well in advance to avoid any location or course which might lead to collision. When collisions or near-collisions occur under such circumstances, there is usually a surprise element due either to failure to detect an intruder or failure to analyze visual cues correctly or in time.

Collision situations in which the fixity-of-bearing criterion is applicable occur generally under cruise conditions. If the intruder is sighted reasonably early, there is time, if closing speeds are moderate, to evaluate the threat and determine what action, if any, is needed. In principle, it should be possible to devise rules-of-the-road which, when fixity of bearing is observed, will insure that a reasonable avoidance action is taken, and that if both aircraft maneuver the maneuvers will be complementary.

Such rules-of-the-road are of limited value when aircraft are maneuvering, and the complex nature of the situation near airports requires a much greater degree of flexibility and improvization than any set of rules could provide. The question is what rules could best cover general cruising conditions.

One such set of rules is incorporated in the CAR, part 60, as follows:

1. When two aircraft are approaching head-on, or approximately so, each will alter its course to the right.

2. An overtaken aircraft has the right of way, and the overtaking aircraft will alter its course to the right.

3. When two aircraft are on crossing courses at approximately the same altitude, the aircraft which has the other on its right will give way so as to keep clear.

An aircraft which has the right of way may ordinarily maintain its course and speed, but the pilot is not relieved of his final responsibility for taking action necessary to avert a collision. An aircraft obliged by the crossing rules to "keep out of the way" is expected to avoid the other without passing above, below, or ahead of him, unless passing well clear.

These right-of-way rules, identical for day and night flight, raise a number of problems. There is nothing to insure that the "responsible" pilot (the one not having the right of way) will see the aircraft having the right of way, whose pilot expects to continue his heading and airspeed, at least until a more critical moment. At what angle does "approximately head-on" change to "crossing," where the rule is different? And does "give way" mean to turn, climb, descend, or change speed? What happens when an overtaken aircraft decides to turn right, and so loses its right of way?

The rules-of-the-road in the CAR were taken from rules-of-the-road devised for marine navigation. There is some question whether these rules are adequate even for marine use. There can be little doubt that the important differences between air and sea navigation require different rules for the air (Calvert, 1961).

The time available after sighting for decision and maneuver in the air is very much less than on the sea. Where time-to-collision at sea may be measured in minutes, it is measured in seconds in the air. With so little time, and with sighting failures not uncommon, every pilot should have avoidance responsibility at all times, regardless of "right of way."

Ships at sea can control speed over a wide range, while aircraft (except helicopters) have only a limited range of control and cannot drop below a minimum speed which itself is many times higher than marine cruising speeds.

Ships at sea can maintain alert watches in all directions, without difficulty, and generally can assign to watch duty personnel who have this as their sole function. Pilots may have copilots to share observation duties, but limitations on cockpit visibility and the many other functions required of pilots (and copilots) limit the amount and the effectiveness of the attention that can be given to collision avoidance.

On the other hand, aircraft operate in three dimensions and so have the important possibility of altitude avoidance. Altitude maneuvers are often used by pilots to avoid collision, but the present rules-of-the-road do not take this maneuver into account.

To design rules-of-the-road unambiguous about pilot responsibility, insuring complementary maneuvers, and providing the most effective maneuver for all possible collision situations, is by no means a simple task.

A complicated set of rules, based on a detailed analysis of sight bearing, closure speeds, and required magnitude as well as direction of maneuver, was devised by de Vienne (1956). When a maneuver is indicated for either or both aircraft, it is always a right-hand turn, followed by an equivalent left-hand turn to get back on course.

Calvert (1960) devised a set of avoidance maneuvers which called for combined turn and altitude change maneuvers, to be used whenever fixity of bearing indicated a possibility of collision.

One interesting set of rules for avoidance in a horizontal plane, is based on the principle that a pilot maneuvers so that the sight line between himself and the intruder, if the intruder course is not changed, rotates counterclockwise. (The intruder drifts to the left in his field of view.)

This proposal has been analyzed by Hollingdale (1961) and Calvert (1961). Figure 5 is a course diagram illustrating the manner in which this system operates. In general, both aircraft are required to maneuver, and maneuvers consist of turns, in specified amounts, and speed changes. As designed, the system is principally applicable to marine navigation, and is particularly well suited to ships with navigation radar equipment. Although based on the simple requirement of counterclockwise rotation of the sight line, its application to air navigation is complex and difficult for some approach directions. The system does not conflict with present rules-of-the-road in that the aircraft on the right passes ahead of the other aircraft; the head-on and overtaking rules would be essentially unchanged.

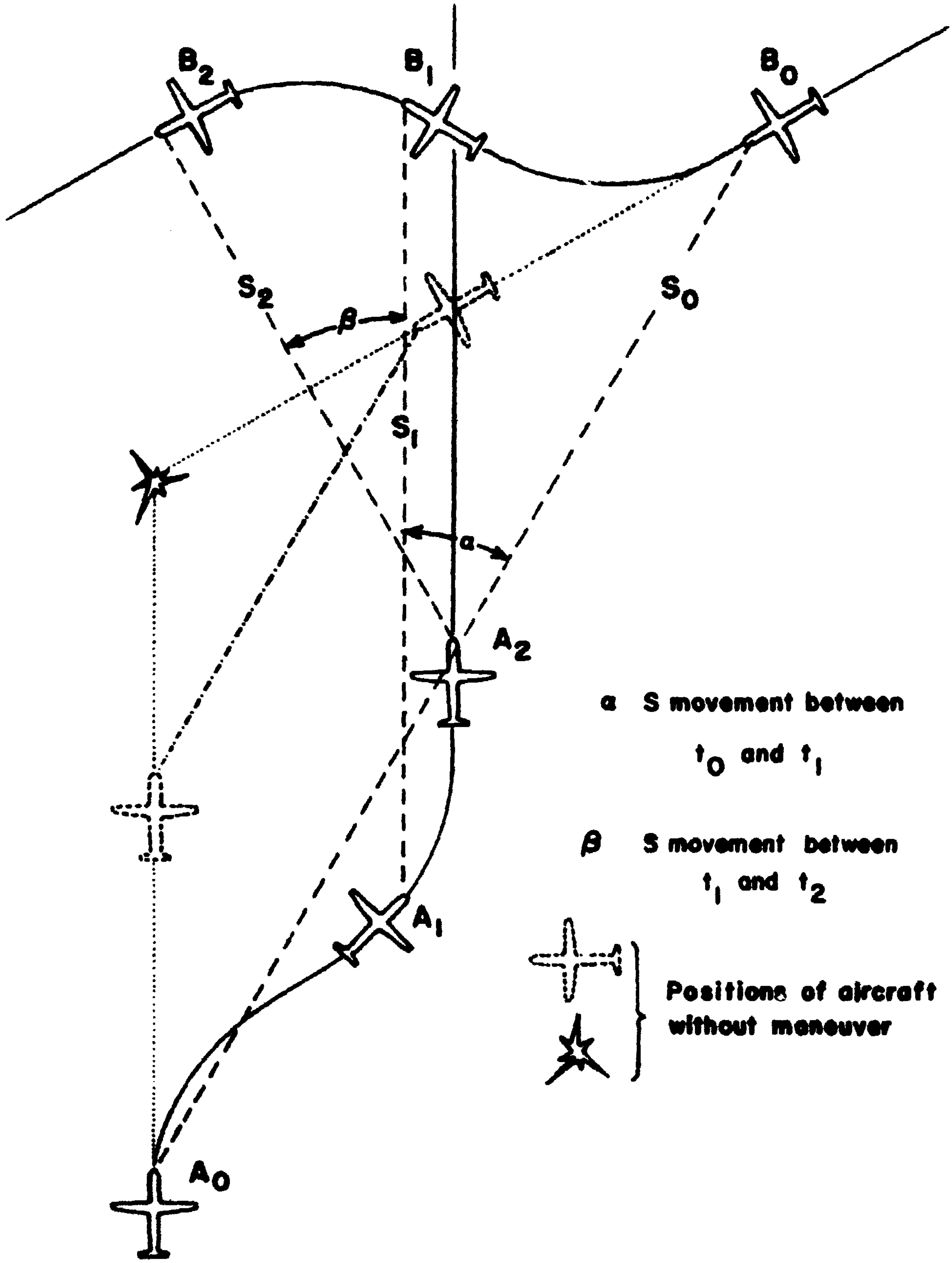

Fig. 5. Illustration of rule requiring counterclockwise rotation of sightline S, between aircraft. Subscripts refer to given times during problem. Problems begin at time zero (t_0) when maneuvers are started. Time 2 (t_2) is time when collision would have occurred if neither aircraft had man-~~uvered.

To sum up, while no set of rules-of-the-road has yet been devised that may be considered completely satisfactory for collision avoidance, it is evident that the present rules do not take advantage of the possibility of altitude avoidance, and in most cases they put the burden of responsibility, at least initially, on only one of two aircraft involved.

X. PROCEDURES FOR EVALUATING AIRCRAFT NAVIGATION LIGHT SYSTEMS

From the time when position lights were first installed on aircraft until about 1940, little interest was displayed in critical examination of the adequacy of the system or in the development of improved systems. Beginning about that time, efforts were made to improve the basic system by various flashing arrangements, by adding lights to the basic position lights, and by moderate increases in intensity.

During the 1950s, interest in improving navigation light systems increased greatly and was accompanied by the introduction of many proposals for new systems, some containing novel features differing radically from existing systems. There were no guidelines by which these proposals might be evaluated and no systematic procedures or facilities for dealing with them.

To facilitate experimentation by inventors and operators who were anxious to test some of the proposals, Special Regulations 361 and, later, 392, were issued, authorizing installation of nonstandard systems, in limited numbers, for the express purpose of collecting information from what might be called "user tests." However, the "experimentation" carried out under this program was haphazard. The reported results were fragmentary and generally consisted of little more than opinion polls and testimonials obtained under unknown and generally doubtful circumstances. Accordingly, at its last termination date, June 25, 1962, SR 392 was not extended.

Generally, the approach to improving navigation light systems has suffered from a preoccupation with "hardware." This has had two unfortunate results. Those proposals accompanied by developed equipment received a great deal of attention, but only in terms of the "package," without serious effort to separate engineering detail from the essence of a proposal. On the other hand, proposals of considerable merit, not embodied in demonstrable hardware, were largely ignored.

By the middle of the 1950s, more systematic approaches were undertaken, and there was some criticism of the inadequacy of customary experimentation. Wright Air Development Center contracted for a broad study of exterior lighting (Laufer, 1955), which resulted in an excellent account of the relation between collision geometry, required warning time, light intensity, atmospheric condition, and visibility.

In 1957, the Douglas Aircraft Company issued a report in

which factors involved in the evaluation of navigation light systems were analyzed. In a subsequent report (Ziedman, 1957) these factors were considered further and the requirements for evaluation procedures were elaborated.

Also in 1957 the Bureau of Aeronautics contracted for a systematic evaluation of several navigation light systems, which resulted in the development of objective test procedures (Robinson, 1959; Fisher, Noffsinger, & Robinson, 1958). Projector (1958b; 1959a) analyzed various factors characterizing navigation light systems and stressed the need for dealing with them separately.

In 1958 the Airways Modernization Board contracted for a study of the status of navigation light systems (Projector & Robinson, 1958). Sharply critical of the experimental procedures that had been in general use, this study suggested very strongly that evaluation procedures, to have value, must be systematic and objective. The present contract was an outgrowth of this preliminary study. One of the tasks under the contract called for the design of a systems evaluation program having as its goals (a) maximum reliability, (b) objectivity, (c) minimum cost, and (d) maximum generality.

To achieve these goals, a large part of the effort has been directed toward obtaining general information which can be applied to the evaluation of any system. Another part has been to develop experimental facilities at the National Aviation Facilities Experimental Center (NAFEC), in cooperation with NAFEC personnel. These experimental facilities plus others available at NAFEC could be used in an evaluation program.

A considerable amount of basic information has been accumulated, and has already served to provide criteria by which lighting systems have been evaluated. Such information is by no means complete, and can never be complete because of advances in the state-of-the-art, new formulations of research questions requiring new information and so forth. Ongoing programs should continue to fill major gaps.

Rigidly detailed procedures for evaluating proposals cannot be established. Each proposal will require individual handling. It is nevertheless possible to set forth general guidelines which will suggest a rational, step-by-step program. In a given case, steps may be omitted, or modified. The objective always should be to use as much existing information as is applicable, to avoid expensive or difficult procedures when inexpensive, simple ones will serve, and to consider all aspects of the problem, including those (such as regulatory problems) that often escape the attention of inventors.

The first step in evaluation is a detailed analysis of the proposal in terms of the information it conveys, the light-coding technique used to convey it, and engineering and economic considerations. These separate elements are then evaluated in terms of information available. It is often possible to reject a proposal on the basis of this analysis, if, for example, it attempts to present information known to be without value, or if it employs a light-coding technique known to be subject to excessive interpretation error, or if its cost is inordinately high. If the system cannot survive such analysis, no further evaluation should be done on it.

However, it may be determined that some defects of the system as proposed are not basic. For example, engineering defects might be corrected, or a system conveying useful information with a poor light-coding technique might be acceptable if a better method of coding were used. In such cases it may be desirable to proceed with evaluation of the acceptable parts of the proposal, or to redesign it to make it more acceptable.

If corroborative information or test data has been submitted with the proposal, this should be critically examined as part of the analysis. Test data, in particular, should be evaluated for objectivity, adequacy of test design, and reliability of results.

If a proposal survives the analytic screening, it is then subjected to experimental investigation. This may include, as needed, photometric and engineering measurements, visibility tests, or psychological tests. As much as possible, essential aspects of the system should be examined separately. It is not possible to specify in advance precisely what tests will be needed, but generally laboratory, simulator, or field tests are to be preferred to flight tests. It is not always possible to avoid flight tests, even for preliminary screening. In any event, if a proposal survives preliminary screening, it must ultimately be subjected to extensive flight tests before it can be considered as a new standard system under the regulations.

At all stages in the investigation a prime consideration must be that no system offering only minor or doubtful improvement over the standard system passes the screening process. The results may be interesting and may add to the fund of information to be used in subsequent evaluations, but changes in the regulations which would modify a standard system should not be undertaken except for substantial gain.

XI. NAVIGATION LIGHT SYSTEMS AND THE CIVIL AIR REGULATIONS

Two apparently contradictory generalizations describe the present situation:

1. In several respects navigation light systems are much less effective than has been generally assumed.

2. Navigation light systems can be made much more effective than they now are.

The technical background on which these generalizations are based has been summarized above. Technical aspects of navigation light systems are inextricably linked with the CAR, and the effectiveness of light systems often depends critically on the regulations and how they are administered.

The Need for Standardization

The effectiveness with which navigation light systems provide communication between pilots depends largely on the speed and accuracy with which their "language" can be read.

Before a pilot takes a new model of an aircraft off the ground, he becomes thoroughly conversant with its instruments, controls, indicators, warning devices--its internal communication system. He continues his training in flight and is tested before he is assumed fully competent. Pilots require similar training in using navigation light systems. They must learn to "read" the information accurately and quickly, and to make correct decisions based thereon. A pilot sighting a signal constituting part of a navigation light system on an aircraft need not have been trained in operating that aircraft, but he ought certainly to have been trained in using the signals he sees. A pilot flies his own aircraft with the aid of its internal communication system, but his navigation lights are part of a communication system used by other pilots.

In these circumstances standardization is essential. With high-speed aircraft the time available for making decisions is often insufficient under the most favorable conditions. Under many marginal conditions any loss of time caused by lack of standardization may decisively determine the outcome.

Essentially, present navigation light systems, in addition to indicating the aircraft's presence, are intended to identify azimuthal sectors around the aircraft. To provide

this relatively simple information, a pilot may be confronted with a great variety of signals and combinations of signals, including steady red, green, and white lights; flashing red, green, white, yellow, and bluish-white lights; alternately flashing red and white, yellow and white, green and white, red and green lights; bluish-white lights flashing at any of three different frequencies; lights flashed sequentially in rows; and many other arrays and combinations of lights too numerous and complex to list here. The first task of a pilot confronted with a light signal should be to "read" the information. In the present situation he must first, instead, identify the system to which it belongs. This is often difficult; it is sometimes impossible, because the same signals appear in different systems with different meanings.

Lack of standardization has superimposed on the pilot's already difficult task a superfluous task, characterized by three possible degrees of difficulty:

1. At the very least, he must identify the system to which the light signal belongs--sometimes easy, but in any event a task that should not be necessary.

2. The pilot is confused by the need to determine the system to which a signal belongs. He must know all possible systems in detail and be able to place the observed signal unerringly within the correct system. With some signals this is theoretically possible, but often the diversity of systems leads to delay, uncertainty, or error.

3. If there is a definite ambiguity, the pilot cannot resolve it unless and until he gets additional information from the light system.

Lack of standardization may also make it more difficult to distinguish aircraft signals from lights on the ground, many of which are similar to those found on aircraft. This confusion can be reduced by reducing the number of different kinds of aircraft light signals.

The first step is to achieve standardization at the earliest practicable date--meaning that every aircraft shall have all of the standard system and nothing else. This does not mean, necessarily, that every aircraft would have an identical system; different detailed configurations may be permitted (even called for) on different aircraft. It does mean that each authorized configuration would be part of an over-all unambiguous standard, whereby a pilot sighting an aircraft light signal could interpret it without hesitation or uncertainty.

Heretofore, navigation light systems have been judged outside the context of standardization. It has not been appreciated that the virtues of any system, however great when considered in isolation, are lost or seriously diluted if such a system is one among several being flown simultaneously. The one criterion by which any system ought to be judged is its suitability as the standard system.

Before taking up the details of a program intended to achieve and maintain genuine standardization, it is useful to consider some general aspects, particularly two technical areas of special importance: the role of intensity as related to the CAR, and the limitations of visual collision avoidance with navigation light systems.

Problems and Procedures in Standardization

Once genuine standardization has been achieved, any subsequent major change in regulations should require converting all aircraft to the new standard. Thus, it would be ill-advised to change regulations frequently or for minor gains incommensurate with the cost of refitting. Promising new systems should be tested and proved with sufficient thoroughness that when one does become the standard, there is reasonable assurance it can remain standard for a number of years thereafter. It is impossible to guarantee that greatly improved systems may not be developed or discovered very soon after a standard is made effective, but it is entirely possible, through painstaking evaluation, to avoid hasty or inadequately supported changes.

There are special difficulties in requiring standardization of small, low-powered aircraft, which often have power plants too small for a complete standard system. While it is highly undesirable to grant exceptions for this reason, it may nevertheless be unavoidable. In any event, the authorized exception should be a version of the standard, with similar signals, free of ambiguity.

High-performance aircraft also present difficulties. Conventional locations for lights are often unavailable, or else are subject to severe restrictions of weight, size, and environmental factors. At the high speeds of such aircraft, the limitations of visual collision avoidance are so great that is is unreasonable to impose a difficult lighting requirement on them. However, they land and take off at moderate speeds, often mixed in with conventional traffic. In VFR mixed traffic at moderate speeds, the lighting requirements should be the same as for other aircraft. Recent engineering advances, including retractable anti-collision lights and very small high-powered position lights, suggest that standard navigation light systems for high-performance air-

craft will be feasible (Godfrey, 1959; Grimes drawing G-8450).

Aircraft with unusual flight characteristics, such as helicopters, VTOL's and dirigibles, might require distinctive lighting systems. Any such systems should be standardized and should dovetail with the standard system on conventional aircraft.

Once standardization has been achieved, any contemplate change must be examined for confusions or ambiguities that might arise during the transition from the existing to the new standard. It has been the practice to allow relatively long periods of time between promulgating a regulation and putting it into effect. This transition time probably canno be avoided, especially with a major change. Ambiguities suc as exist today should be allowed only for overwhelmingly cogent reasons. In any event, transition periods should be kept to a minimum. It may be possible to provide relatively long delays before new regulations become effective, but to confine the actual changeover time to a short period just before the effective date.

Standardizing air traffic internationally would require cooperation of all national regulatory agencies through the International Civil Aviation Organization. This aspect of the problem has not been stressed in this report, because the diversity of systems within the borders of the United States is almost entirely domestic in origin. While there is some diversity in foreign aircraft, virtually every system appearing on foreign aircraft also appears on American aircraft. Ultimately, when the United States is prepared to attempt genuine standardization, the effort should be coordinated with other countries through ICAO.

Intensity and the CAR

It was shown in Chapter IV that the navigation light intensities called for in the CAR are marginal. The minimum requirement of 100 candles for the anti-collision light in the horizontal plane provides a visual range of about 2-1/2 miles when atmospheric conditions are minimum VFR (3-mile visibility). The minimum intensity of 5 candles for the wing position lights from 20 to 110 degrees outboard gives a visual range of only 1-1/4 miles, based on the "practical" threshold, and must be considered submarginal. Substantial increases in intensity for all navigation lights would be of considerable value.

Since the CAR prescribe only minimum intensities, an aircraft operator may install equipment of much higher intensity without deviating in any way from the requirements.

Nevertheless much of the effort toward developing improved systems has been directed toward higher-intensity systems not in accord with the regulations, in the mistaken belief that this was the only way to obtain higher intensity. As indicated earlier, any system can be designed for higher intensity if the designer is willing to pay the price in terms of increased power consumption. In achieving and maintaining genuine standardization, it is unnecessary and undesirable to depart from the standard in order to increase intensity.

CAR requirements for the intensity distribution of position lights at various angles from dead ahead are shown in Table 4. The higher requirement forward is based on the fact that collision courses in these directions, for any given aircraft, involve higher closing speeds than those from other directions. Therefore to provide a given warning time, sighting ranges must be greater and signal intensity must be correspondingly greater forward. Laufer (1955), analyzing the intensity requirements as related to collision-course convergence angle and aircraft speeds, obtained results which suggest that the abrupt drop in required intensity 20 degrees outboard is not justified.

But the problem is far more complicated. Slow aircraft may collide with fast aircraft. The required distribution of intensity around the slower aircraft, for equal warning time, is much more uniform than for the fast aircraft. In the limiting case, a hovering helicopter for example, the intensity requirement should be uniform in all directions. In the case of a fast aircraft in a collision situation with a slow aircraft, no rearward intensity is required since the slow aircraft cannot overtake the fast one. Depending on the speed ratio, the zero-intensity zone may extend well into the forward hemisphere; the required intensity ratio under these circumstances is infinite. Finally, at very high aircraft speeds, visual collision avoidance may be difficult or impossible, or the signal intensities required may be far beyond practicability.

The implications of the above for the CAR will be treated in detail later. Two general conclusions may be stated:

1. Intensities should be generally increased.

2. Position light intensities, especially in the zone from 20° to 110°, should be increased substantially.

Limitations of Visual Collision Avoidance

A number of factors limit the usefulness of efforts to

Table 4

CAR Minimum Intensity Requirements for

Position Lights

Angle, left or right	Light	Minimum intensity, candles
0° to 10°	wing position, left red, right green	40
10° to 20°	"	30
20° to 110°	"	5
110° to 180°	tail, white	20

avoid collision by visual techniques. In designing light systems and in drafting regulations prescribing standard systems, it is essential to understand precisely what a system can and cannot do. In some cases, the limitations are inherent and not subject to control. In other cases improvements are possible, through more effective use of existing or readily available equipment and procedures.

It has been suggested that the limitations of visual avoidance are so great that it must be considered seriously inadequate or, often, not possible at all (Emerson et al., 1956; Calvert, 1958; Fiore, 1959). It is felt that such positions are in some respects extreme. The limitations of visual avoidance are indeed serious, but to a considerable extent, improvement is feasible. In any event, visual methods are still required and will be used for a long time; the problem is to maximize their efficacy and recognize and define the limitations.

Cockpit visibility. Most cockpits lack sufficient visibility. Pilots are "blind" in many directions and can see in some other directions only with a degree of strain (Edwards & Howell, 1956; Fisher & Howell, 1957). Visibility is particularly poor rearward and is often severely restricted vertically. In some cases climbing or descending overtaking courses involve visibility angles blind to the pilots of both aircraft. It is not surprising therefore that the preponderance of accidents involve overtaking or rear-approach situations in spite of the fact that closing speeds are much slower for such courses (Fisher & Howell, 1957). It is not suggested that these are the only reasons for the high incidence of overtaking collisions. Rules-of-the-road and traffic management result in relatively unidirectional traffic in high density locations, thus providing many more opportunities for overtaking collisions. The combination of high opportunity rates with serious impediments to adequate vision probably account for the preponderance of this class of collisions.

It is possible that rear-view mirrors or other optical devices may help to provide visibility in the otherwise blind directions (Fisher, 1957; Howell, 1958). These are of limited usefulness and require extra attention on the part of the crew member who uses them. Nevertheless since more time is generally available and required ranges are therefore shorter for such collision approaches, even limited advantage gained from such devices may be helpful.

The quality of the glazing itself may have an important effect on visibility. Windshields of extremely low pitch, as on high performance aircraft, have low transmissions and consequently seriously reduce visibility. At a pitch angle

20 degrees from horizontal, for example, the transmission of double glazing is about 45% (Fiore, 1959).

<u>Pilot attentiveness</u>. Collision threats may occur in VFR <u>flight at any time</u> and from any direction. Therefore, a pilot can use visual collision-avoidance techniques only to the extent that he is able and willing to pay constant attention. But the workload of pilots is so severe that they are often too distracted to be able to search regularly and effectively. In the neighborhood of airports, where traffic density is heaviest and collision likelihood greatest, workloads are particularly heavy. Marshall and Fisher (1959), in an experiment on the daytime conspicuity of small aircraft in a terminal area, found that pilots often failed entirely to notice small aircraft on a collision course. When they did detect the intruder aircraft, they often failed to note that it was on a collision course and thus took no evasive action. The pilot subjects in this test had been instructed to watch for and avoid local traffic, but were not aware that their ability to do so was the subject of interest in the test. While the small target aircraft were by no means very easy to see--more often than not they were detected at short but relatively safe ranges and were avoided by effective maneuvers--the number of occasions when they were not detected or not recognized as threats suggested very strongly that pilot distraction interferes seriously with collision-avoidance duties or that many pilots need to allot more time and attention to possible collision threats.

The obverse of the problem presented by the heavy work load of pilots is that resulting from inattentiveness during times when conditions are "too" favorable. It has been suggested that good weather, comfortable physical environment, and the monotony of long, uneventful cruising can seriously diminish a pilot's attentiveness to his tasks and his ability to detect and respond correctly to unexpected and infrequent stimuli (Trumbull, 1962).

Measured in terms of the probability that any aircraft will be involved in a collision at any time, the risk is extremely low, even in high-density areas. But the consequences of collisions are often disastrous. A pilot flying VFR is presumed to be capable of avoiding collisions by visual techniques, and he is responsible for doing so. But to the extent that a pilot does not watch alertly for other aircraft, he cannot be considered <u>effectively</u> under VFR, no matter what his technical status.

The difficulties of collision avoidance, especially in the presence of high-speed aircraft, require that the pilots of both aircraft be responsible for avoidance. It can be of little solace to a pilot involved in a collision that he had

the right of way. The entire concept of right of way, derived from marine traffic rules, is antiquated even for the environment for which it was formulated. In the complex, high-speed environment of air traffic, it can be dangerous. It is the obligation of every pilot, whether he himself is flying VFR or under traffic control, to utilize his visual capability at all times that atmospheric conditions permit.

Sector information. Azimuthal sector, or aspect, information is coded into all systems currently in use or proposed. Although it has not been specified in what way, it has generally been taken for granted that pilots could use such information to determine whether a collision course exists. Analysis has shown, however, that pilots can make such determinations only crudely, even if extremely precise sector information were coded into the system (Calvert, 1958; Applied Psychology Corporation, 1961a). Marshall and Fisher (1959) found that pilots were unable to use aspect information to determine the existence of a collision course. Although they speculated that this inability may have been due to the small size of their target aircraft, it seems much more likely that aspect information is inadequate for the purpose.

Although sector information cannot be used for precisely determining collision hazard, it can serve to segregate aircraft into those with which it is impossible to collide and those which will require further attention. And especially in terminal areas where pilots must keep track of a number of aircraft, it can be helpful in anticipating their probable future locations.

Sector information also permits segregation of collision possibilities into categories of urgency, but again very crudely.

To facilitate these rough screenings, sector-coded systems should be quadrantal, distinguishing left from right and forward from rear aspects. The screening rules to be used with quadrantal sector coding are:

1. If to your right you see the intruder's right, or to your left, his left, no collision impends.

2. If to your rear you see his rear, no collision impends.

If the possibility of collision cannot be ruled out by the above rules, then the urgency of the situation may be classified as follows:

1. If in your forward hemisphere you see his forward

aspect, the situation is likely to be urgent.

2. If to your rear you see his forward aspect, or if forward you see his rearward aspect, the situation is likely to be less urgent.

Obviously these judgments can be refined by feeding into the problem the precise bearing, relative to one's own aircraft, on which the intruder is sighted, and the knowledge of one's own aircraft speed.

It may appear that categories could be further refined by coding more finely divided sector information into the system. However, the results of the analysis show (a) it is difficult to use precise sector information, (b) codes giving more information grow increasingly complex, (c) other information better suited to the purpose is available, and (d) other kinds of coded information might be more useful. These considerations suggest that quadrantal information is optimal for sector coding.

<u>Use of the fixity-of-bearing criterion.</u> Limitations on the use of the fixity-of-bearing criterion were discussed in Chapter II. They are:

1. The criterion is valid only when both aircraft are on straight-line, constant-speed courses. A pilot knows whether his own course meets this requirement but often is uncertain about the intruder's course.

2. There is no experimental data on the ability of pilots to detect movement of the sight bearing. Laboratory experiments show that observers can detect relatively small signal movement, of the order of 1 minute of arc per second (Leibowitz, 1955). In an operational situation, detection thresholds are undoubtedly very much higher, principally due to the instability of the pilot observer's frame of reference. Calvert (1958) has estimated thresholds to be about 0.4 degree of arc per second, but this must be verified experimentally. The operative threshold profoundly affects the ability of a pilot to use the fixity criterion successfully (Applied Psychology Corporation, 1961a).

3. Because of uncertainties due to the difficulty of precise determination of fixity, the fixity-of-bearing criterion is probably of limited value at longer ranges or at high closing speeds.

4. Flashing signals adversely affect the precise determination of the existence of fixity.

In spite of the above limitations, the fixity-of-bearing

criterion is one of the principal avoidance techniques available with navigation light systems, and pilots should make full use of it, while at the same time recognizing its limitations.

High-speed aircraft. High-speed aircraft impose serious limitations on visual collision avoidance. At high speeds, aircraft are slow to respond to maneuver control, and the maneuvers themselves are slow relative to the speeds. For many collision convergence angles, closing speeds are so high, even when one aircraft is much slower than the other, that the possibility of successful visual avoidance is limited. If both aircraft are high speed, closing speeds may be so high that the small possibility disappears altogether, and the outcome of a potential collision situation may be beyond the pilot's control. The closing speed of two aircraft on a collision course depends so critically on the convergence angle that visual collision avoidance cannot be said categorically to be impossible with high-speed aircraft, although it may be impossible under certain conditions.

A number of factors operate in favor of visual collision avoidance, even for high-speed aircraft. If certain altitudes are reserved for traffic in one general direction, the range of possible closing speeds is held down to more manageable levels. (On the other hand, overtaking approaches are particularly difficult from the point of view of cockpit visibility.) At lower altitudes, especially in terminal areas, high-speed aircraft are generally operated at relatively low speeds. A pilot usually knows little or nothing about other aircraft in his vicinity, but his knowledge of his own aircraft may serve to lessen his problem. If his is a very high-speed aircraft he may sometimes be assured that no aircraft will overtake him, but that he could easily overtake others. If his own aircraft is very slow, he must expect trouble from any direction.

The limits of VFR. Part 60 of the CAR, Section 60.30, gives VFR minimum weather conditions as shown in Table 5. Flight visibility is defined in Part 60 as "the average horizontal distance that prominent objects may be seen from the cockpit." In the recently issued Federal Aviation Regulations, Part 1 (1962), this definition was revised to "the average forward horizontal distance, from the cockpit of an aircraft in flight, at which prominent unlighted objects may be seen and identified by day and prominent lighted objects may be seen and identified by night."

The revised definition provides for nighttime observations of lights, but the original operational difficulties of the daytime definition are substantially unaffected. Also, the addition intended to cover night operations is exceedingly

Table 5

Minimum Flight Visibilities

Area	Flight Visibility
Control zone	3 miles
Control area and transition area	3 miles
Continental control area	5 miles
Outside controlled airspace	1 mile

vague. It has been shown that the actual visual ranges of aircraft in the daytime are less than the "flight visibility," and often very much less (Applied Psychology Corporation, 1961b). The designation of "prominent lighted objects" as targets for observation of flight visibility at night is inexact, since the principal determinants of visual range are the intensity of the lights and the background against which they are seen; prominence of the object is irrelevant.

Even if the definition were precise, it is difficult to assess atmospheric conditions to determine their suitability for VFR operation. Atmospheric conditions vary considerably from time to time and from place to place. Ground observations are of particularly limited use in determining flight visibility (Douglas, 1953). Direct estimate of flight visibility by pilots in flight is difficult because of the general lack of "prominent objects" at known distances. At night, it is even more difficult.

It is possible to train pilots to improve their estimates of flight visibility from the meager cues sometimes available, including the amount of backscatter from their own lights, but at best such estimates must be considered crude.

A note in the CAR Manual, part 60, sect. 60.30, suggests that the prescribed minimums be treated conservatively by pilots: "Good operating practice requires that regular or continued flight in near-minimum weather conditions be avoided." It may be desirable to call for even more conservatism. Figures 3 and 4 in Chapter V suggest that when the equivalent daytime visibility is 3 miles, a 100-candle light signal will be visible just under 3 miles at night. But for an equivalent daytime visibility of 5 miles (the minimum for the continental control area) the visual range of the light will be less than 4 miles. Furthermore, if the background is relatively bright (moonlit sky or dusk) the visual range will be appreciably reduced. However, if signal intensity is raised to 1000 candles, then the visual range of the lights will correspond well with daylight visibility, even if the observing conditions are not ideal.

The limitations of visual collision avoidance suggest the advisability of raising VFR minimums above their present levels, in order to insure longer sighting ranges and therefore more decision time. It may also be advisable to specify more particularly the limiting conditions of VFR, not only as related to atmospheric conditions but also to the speed of the aircraft, the range of possible closing speeds as determined by air traffic rules, and the intensity of the navigation lights carried. While this may seem excessively complex, the limitations of collision avoidance are correspondingly

complex; the alternative is extreme conservatism, eliminating a large range of relatively safe conditions in order to eliminate rare risks, or else exposure of aircraft to occasional situations in which visual collision avoidance is not possible.

A convenient and more conservative demarcation between VFR and non-VFR atmospheres might be the boundary between "light haze" and "clear" (see Fig. 4, Chapter V). At this boundary the transmissivity is 0.53/mile and the daytime visual range is about 6 miles. The visual range of a 1000-candle signal light is slightly greater than 6 miles. If the assumptions about the fixity-of-bearing criterion made in Applied Psychology Corporation Technical Report No. 1 (1961a) (that is, threshold detection angle = 2° and escape acceleration = 1/4 g) this sighting range is probably adequate for lower ranges of probable closing speeds, not in excess of about 400 or 500 miles an hour, but even this must be considered marginal. It is likely to be practicable under favorable conditions, if head-on convergences can be eliminated by traffic rules.

XII. POSSIBLE CHANGES IN THE CIVIL AIR REGULATIONS

The following discussion assumes that effective and genuine standardization will be the first objective of any change in the CAR. The formidable problems involved often make it difficult, even impossible to effect changes of unquestioned value. These problems will be considered and changes in the rules which can achieve fundamental objectives with minimum impact on the aviation community will be outlined.

Three phases are considered:

Phase I--Regulatory action to achieve genuine standardization under present conditions.

Phase II--Improvements on the standard system achieved in Phase I, calculated to obtain optimum performance within the basic intent of the design.

Phase III--More or less radical major or long-range improvements in the standard system, having substantial impact. This long-range program should lead to regulatory changes only if the improvements are proved in careful, extended evaluation, and are commensurate with the cost and other considerations.

Phase I should be instituted with minimum delay. The timetable for Phases II and III should be flexible. Phase II, depending on considerations discussed below and on the time required to effect Phase I, may be combined with Phase I in order to avoid a change in the regulations too soon after the completion of Phase I.

Phase I: Regulatory Action to Achieve Genuine Standardization

All navigation light systems being flown today provide sector-coded information. To achieve genuine standardization without scrapping all present systems, it is necessary to examine each for adequacy and to consider which (or which elements) would constitute the basis for a regulated standard system meeting the following criteria: (a) provides adequate sector information, (b) requires little or no development involving extended evaluation of doubtful outcome, (c) has minimum impact on the aviation community, (d) in terms of available equipment, sacrifices no important attributes such as intensity or reliability, (e) permits smoothest and fastest transition.

The system that comes closest to satisfying these requirements is apparently the one prescribed by the present CAR: steady-burning red, green, and white position lights and one or more flashing red anti-collision lights.

Anti-collision lights are omnidirectional: equally visible in all azimuthal directions. The angular coverage of the position lights is as follows:

red wingtip: 0° to 110° left
green wingtip: 0° to 110° right
white tail: 110° left around the rear to 110° right

This 3-sector system does not provide optimal quadrantal sector coding, since the white light in the rear does not distinguish left from right. Also, the sector boundaries abeam are at 110° instead of 90°.

However, no system now in use provides better sector information. Some use additional lights, as on the fuselage, providing an array that may enable pilots to interpret sectoring more precisely or even to distinguish left from right to the rear, but array codes, as noted earlier, are confusing and unreliable.

Since the system has been in use for several years, many, perhaps most, aircraft already have it; thus, no development is needed. For similar reasons, the impact on the aviation community would be less than for any acceptable alternative. Large numbers of aircraft already fly the system; many others would require only minor changes, such as disconnecting excess lights or bypassing flashers.

Two major groups of aircraft might require changes of some consequence: the small number carrying nonconforming equipment which would have to be replaced entirely; and the aircraft having position lights but no anti-collision lights, this latter group including many small, private aircraft. The cost of one or in some cases two anti-collision lights might seem large to these owners. More important, the limited power capacity of these small aircraft would prohibit adding more electrical equipment. For genuine hardship cases solutions might have to be worked out, but no acceptable alternative would involve less hardship.

Table 6 compares approximate costs of some of the systems and components of interest (only the equipment cost is given; installation costs vary considerably).

As for the requirement that no important attributes of current systems be sacrificed (in other words, that the standard not represent a step backward), the present system

Table 6

Approximate Costs of Navigation

Light System Equipment

Proposed Standard System	
Position lights (three required)	$ 15 each
Anti-collision light (one or two required)	$ 100 each
Cost of complete system	$ 150-250
United Air Lines*	
Oscillating position lights (three required)	$ 375 each
Cost of complete system	$ 1100
Honeywell-Atkins	
Two wingtip units (Exact costs are difficult to estimate. Designs and prices have varied considerably. This estimate is based on a May 1961 quotation of $2350).	Over $ 2000

* Since this report was prepared, a version of the UAL system has been developed for small aircraft. It is understood that this lighting system will be in a cost category comparable to that of the proposed standard system.

is an acceptable minimum. An alternative that appears to satisfy most of the requirements consists of position lights without anti-collision lights; this is simpler and cheaper than the proposed system, and is already installed on an even larger number of aircraft, but is unacceptable for the following reasons:

1. It would substantially reduce intensity when present minimums appear to be too low. Anti-collision lights are generally more intense than position lights in all directions, and considerably more intense in most.

2. If the position lights were burned steadily, then the conspicuity advantage of flashing lights would be lost. On the other hand, if they were flashed, there would be no steady lights, reducing the effectiveness of the fixity-of-bearing criterion. In the proposed system, the flashing anti-collision light provides the most conspicuous warning of aircraft presence at long range, and the steady position lights are useful as targets for observing bearing fixity at shorter range.

3. The simple position-light system could conceivably be modified to meet the above objectives by using higher-intensity fixtures and pulsating the lights, rather than flashing them with a completely dark off period. By this arrangement, they would appear to flash at long range but would pulsate at shorter range without going out entirely. But such modification would require replacing equipment on almost all aircraft, thereby imposing a heavy burden on virtually the entire aviation community.

The present system meets very well the fifth requirement, enabling a fast, smooth transition. Since burdensome changes are required in relatively few cases, the transition period could be very short. The time required to draft and circulate regulatory proposals, to prepare, submit, and analyze comments, and to hold conferences need not be prolonged by considerations of excessive, burdensome changeovers by the entire aviation community.

Because all pilots are already familiar with the system, no retraining is involved.

It has been suggested that anti-collision lights should be white rather than red. Simple and inexpensive replacement of the red cover glass with a clear cover would yield a white signal with 4 to 5 times the intensity of the red signal. On the face of it, the suggestion appears attractive. It is not recommended at present, however, for the following reasons:

1. Anti-collision lights are mounted behind the cockpit

and project their beams forward directly in front of the pilot. Backscatter, plus occasional direct illumination of aircraft structures in the pilot's view, can be a serious problem. While the effect of backscatter on pilots is not fully understood, it has been found that red backscatter is substantially less bothersome than white, especially in marginal atmospheric conditions. This is explained partly by the much lower sensitivity to red light in the periphery of the eye. While this means that an observing pilot will see the white signal better than the red in the periphery of his eyes, it has been found that the visibility of red signals in the center of the eye is significantly better than indicated by photometric measurements (on which the 4 to 5 times increase in intensity of white over red is based) (Middleton & Gottfried, 1957; Mullis & Projector, 1958). Furthermore, it is seriously questioned that signals are sighted in the periphery of the eye under operational conditions (see Chapter IV). These effects are far too complex and insufficiently well understood to warrant a change to white at this time.

2. The higher intensities being recommended would magnify the deleterious side effects mentioned above.

3. Because it is simple and inexpensive, the change to white could be made at any future time; thus there is no reason to consider it until its desirability is well established.

To require general increases in intensity as part of Phase I would mean replacing the navigation lights on virtually every aircraft. Also, serious problems of installation, wiring, and power might jeopardize the standardization program, and would certainly delay it. Standardization is so greatly needed, and its accomplishment so relatively easy, that it is felt desirable to proceed immediately. However, the need for higher intensity need not be ignored; it can be strongly recommended without being required.

While the CAR prescribe minimum intensities, higher intensities with the standard configuration would in no way violate the regulations, nor depart from genuine standardization. Equipment providing substantially higher intensities is already available or in an advanced stage of development. Some high intensity equipment not in accord with the proposed standard is already in use. In changing to the new standard, there is every reason why operators of aircraft with nonstandard high intensity lights should use equipment which will result in no loss of intensity.

In order to facilitate immediate standardization, it may be inexpedient to require increased intensity at this

time. However, it may be feasible to require all new equipment to meet higher intensity requirements, especially for transport and other large aircraft. The option of operators to equip their aircraft with higher-intensity lights in the interest of increased safety already exists and would remain available after standardization.

The cost figures quoted above are for units conforming to present intensity requirements. Obviously, higher-intensity versions of this equipment will cost more, but there is no reason to believe their cost would be as great as that of other presently available high-intensity equipment.

Phase II: Regulatory Action To Improve The Phase I Standard System

The objective of Phase I was narrowly limited to the essential requirement of achieving genuine standardization at the earliest practicable date. Because it is felt that this could be done without the necessity of developing new equipment, of extended evaluation, or of serious impact or delay, it has been felt desirable to consider improvements in the Phase I system as part of a second phase.[1] Three possible regulatory actions are considered: (a) dividing the symmetrical white tail sector into two parts, in order to distinguish left and right to the rear; (b) increasing minimum-intensity requirements; and (c) changing traffic rules and minimum conditions for VFR in order to increase available warning time in possible collision situations.

Converting the Standard 3-Sector to a 4-Sector Quadrantal System

The major defect of the present 3-sector system is that it does not distinguish left from right in the rear. Also, while the two forward sectors are 110°, a quadrantal system

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1 It is not meant thereby to rule out the possibility that part or all of Phase II might be combined with Phase I in a single regulatory action. Only the regulatory agency itself can decide questions like these, and many factors other than those considered here may underlie decisions. Furthermore, the basis for decisions changes in time, depending on the state-of-the-art, the availability of information, the receptiveness of the aviation community, etc. Thus Phases I and II are separated here because they do seem to involve different elements or elements of differing importance. At the time of making decisions about regulatory action, these factors may be weighed differently than they are now.

with sharply distinguished 90° sectors is considered preferable. It is important, therefore, to change the present system to make it more nearly quadrantal. If has been shown, however, that a sector-coded system is not and cannot be a precision device in visual collision avoidance. Its major function is to enable a pilot to avoid potentially dangerous situations. Once he is in such a situation, sector coding is of little or no use in determining the existence of a collision course or deciding what avoidance maneuvers will be most effective. In short, while the usefulness of quadrantal sector coding makes it worthwhile, the limitations on its usefulness make it desirable to pay special attention to the cost and impact of methods of obtaining it.

The essential change proposed is replacing the 140-degree white taillight with a light or lights covering two 90-degree quadrants to the rear, the left yellow and the right bluish white. To minimize the impact, it is proposed not to require a change in wingtip position lights until they are being changed for other reasons (for example, to increase intensity), at which time their coverage could simultaneously be changed to 90 degrees quadrantal.

Substituting bluish white and yellow for the white signal raises problems, the most important of which is the specification limits for these colors.

In all signal color systems, including the 3-color system of the CAR, an effort is made to permit as much tolerance for the colors as is consonant with easy and accurate identification. There are two major reasons for this: it is difficult to manufacture colored glassware to narrow tolerances, and it is desirable to obtain glassware of as high a transmission as possible. For many colors, notably red and green, high color purity is obtained at the expense of very low transmission. In view of the need for high-intensity signals, the requirement for high transmission makes it especially desirable to determine tolerances carefully.

For the conventional 3-color system acceptable tolerances, worked out over the years, are described in Federal Standard No. 3 as the "Aviation" series of colors. Transmissions for good red and green filters in this series are of the order of 20-25%. White, of course, is obtained with clear glassware. This system is considered acceptable as a 3-color system; it is not intended that Aviation Red and Aviation Green be used in conjunction with more than one other color intervening in the range of yellow to bluish white. Another system is described which is suitable as a four-color system. This system, the "Identification" series, includes red, green, yellow, and "lunar white" (a bluish white), but calls for much purer reds and greens to make

room for yellows and bluish whites of fairly wide tolerances.[1] Identification Red and Green glasses have transmissions approximately half the transmissions of Aviation Red and Green.

It would be possible to change the glass covers of Aviation Red and Green wingtip position lights to Identification Red and Green. This would require changing every piece of equipment now in use, but the cost would be relatively small per unit. More important, however, would be the reduced intensity, a penalty that would be paid with existing equipment as well as new higher-intensity equipment.

If the red and green in the proposed system are in the Aviation series, then there is no existing specification for yellow and bluish white suitable for making up a reliable 4-color system. It is felt that satisfactory tolerances could be specified for these two colors. These tolerances would be appreciably narrower than existing ones, but if carefully determined would be broad enough for reasonable manufacturing. Fortunately, both the yellow and bluish white color limits could be met with glassware of relatively high transmission, of the order of 30-50%.

To sum up, it is felt practicable to add a yellow and a bluish white to the existing red and green Aviation colors to make a 4-color sector-coded system, but color tolerances for these new colors would be different from existing color tolerances for any similar colors. Careful experimentation would be required to determine specification limits for glassware in the new colors to insure a proper balance between adequate color distinctiveness and manufacturing capability.

Another problem with the four-color system is ambiguity in the overlap regions between sectors. (This problem exists at present in the 3-sector system, but would be more serious to the rear in the proposed quadrantal system.)

The overlap dead ahead is not serious. The location of the wingtip position lights at the extremities of the wings means that at almost any distance of observation the two signals, red and green, are seen as separate signals. Not only is there no merging, but the visibility of the two separate signals at and near dead ahead identifies the aspect of the sighted aircraft quite precisely.

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[1] Blue and purple are other available signal colors, but are not considered suitable for long-range signaling systems like those under consideration here.

Abeam, there is greater possibility of confusion, depending on the relative location of the wingtip and tail on any given aircraft and on the distance from the observer. If we take one minute of angle as the minimum separation at which two light signals can be identified as separate (Moon, 1936, p. 423), then if, in a given sighting direction, the lateral separation of a wing and tail light is 10 feet, they will appear as a single light source beyond about 7 miles. In an operational situation, it is doubtful if the eye can resolve two sources as close as one minute of angle, and it is quite unlikely that their separate colors can be identified. But lateral separation is often appreciably greater than 10 feet, and 7 miles, in terms of the usual visual range with present equipment under marginal conditions, is a considerable distance. It is true that in the clearest weather or with high-intensity lights long sighting ranges can be obtained, but it is likely that under most circumstances wing and tail lights will be separable.[1]

When merged, two position light signals are seen as one because the color of the signal is the additive combination of the separate colors. In the case of the present 3-color system, the overlap zone at 110° on the left would appear to shade from red to white through orange and yellow or pink. On the right side, the overlap would shade from green to white through greenish white. In the proposed four-color system the overlap zone on the left would shade from yellow through orange to red. There would be no doubt of its being the left side. If the present wingtip coverage is retained, the overlap zone would extend 20 degrees from 90° to 110° (plus the cutoff regions). If the two signals are separable, then the observer can tell that he is in the 20-degree overlap zone. If the wingtip units are replaced with 90-degree quadrantal units, then the overlap zones are much smaller, as they are at other zone boundaries, their size depending on the sharpness and precision of the cutoffs of the light units involved. The boundary relationships on the right side would be similar except that the color shading would range from bluish white through greenish white and pale green to green.

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1 The merging of light signals is a problem more frequently between an anti-collision light and any position light. The clarity of separate signals is always subject to degradation when merging occurs, but the flashing characteristic of the anti-collision light offers some help in providing a distinction against a steady-burning position light.

The most troublesome boundary would be that at the rear. Here the light signals originate from a single unit or from two units very close together. Merging would occur at all meaningful observation distances and the colors would range from yellow through white to bluish white. To minimize ambiguity, the overlap zones would have to be as small as possible. Ingenious but somewhat complicated techniques for resolving the overlap zone ambiguity in the rear have been proposed, but would have to be evaluated carefully before being considered as ready for application. In any event an ambiguous overlap zone of as little as one or two degrees to the rear is a considerable improvement over the present ambiguous coverage of 140 degrees.

The ability of pilots with second- or third-class medical certificates to distinguish the four colors of the proposed system will require investigation. Holders of these certificates are now required to distinguish Aviation Red, Green, and White. It may be that a few pilots with color vision defects sufficiently minor to enable them to pass the present requirement would have difficulty with the 4-color system.

Transition to a 4-sector system would not present serious problems. The forward sectors would remain essentially unchanged. There would be ambiguity between the white of the present system and the bluish white and yellow of the new system, and a pilot would have to consider his ability to distinguish among these three colors as unreliable. Occasionally, especially if he could observe two or three of the colors simultaneously or in rapid succession, his capacity to identify an observed signal color might be substantially better than normal, but conservative practice would require that he consider the distinction unreliable until he can be sure that the transition is complete and that his choice lies only between yellow and bluish white. During the transition, therefore, quadrantal rear sectors would be of uncertain value--but the pilot would be no worse off than he is now.

Increasing the Minimum-Intensity Requirements

Since most presently available equipment meets but does not substantially exceed present requirements, any significant increase in requirements would mean replacing virtually all present equipment.

If the Phase I recommendation of higher-intensity equipment has been accepted, the impact of a mandatory requirement would be lessened. It is unlikely, however, that many aircraft would be equipped with higher-intensity lights as the result of a recommendation. In view of the hardship involved, regulations might recognize four categories for transition:

1. On new aircraft, the higher requirements could be imposed early and completely.

2. If equipment is being replaced for other reasons (for example, replacing the taillight with a two-color light), the intensity requirement could be raised at the same time.

3. Aircraft might be categorized by class of operation, for example, transport and commercial.

4. For small private aircraft the expense of replacement might be compounded by inadequate power. For such aircraft it might be necessary to impose less stringent requirements.

The present CAR call for minimum intensities for position lights in the horizontal plane (azimuth), as shown in Table 7. Above and below horizontal, the minimums shown in Table 8 are required. To provide reasonable cutoffs in overlap zones, maximum allowable intensities in zones outside the intended coverage zone for a given position are specified, as shown in Table 9.

Anti-collision lights are required to have uniform intensity at all azimuthal angles, with minimums for various angles of elevation as shown in Table 10.

Because of the complexity of collision situations and the extraordinary gamut of conditions that may be encountered, it is difficult to determine precise intensity requirements for an ideal navigation light system. Also, there are practical limitations on the intensities that can be required by regulations on all aircraft.

In drafting regulations it is necessary to consider many factors and to reconcile conflicting requirements. Therefore the higher intensities suggested below are intended as guidelines, setting forth objectives reasonable in terms of the present state-of-the-art and engineering and economic considerations. It may prove necessary or appropriate to reduce the size of the suggested increases or to set up different requirements for different classes of aircraft. It is also worth repeating that the requirements are minimums. Where possible, these requirements may and should be exceeded at the option of the aircraft operator, especially if the recommended increases cannot be imposed by regulations. A further discussion on this point, with specific recommendations, is contained in the next parts of this chapter.

Position light intensity requirements. The present requirements for forward position lights, as shown in Table 7,

Table 7

CAR Minimum Position Light Intensity

in the Horizontal Plane

Direction	Light	Intensity, candles
0° (dead ahead) to 10°	Left red wingtip and right green wingtip	40
10° to 20°	" "	30
20° to 110°	" "	5
110° to 180°	White tail	20

Table 8

CAR Minimum Position Light Intensities

Above and Below Horizontal

Angle above or below horizontal	Intensity[a]
0°	1.00 I
0° to 5°	.90 I
5° to 10°	.80 I
10° to 15°	.70 I
15° to 20°	.50 I
20° to 30°	.30 I
30° to 40°	.10 I
40° to 90°	.05 I

[a] "I" is the minimum intensity in the horizontal plane specified in Table 7.

Table 9

CAR Maximum Position Light Intensities

in Overlap Zones

Boundary	Maximum Intensity, Candles	
	10° to 20° beyond boundary	beyond 20°
0°, red-green	10	1
110°, red-white on left or green-white on right	5	1
0°, red-green[a]	10% of peak	2.5% of peak

[a] Paragraph 4b.634.1, of CAR 4b gives maximum percentages of peak intensity for forward position lights in overlap zones when peak intensities are higher than 100 candles.

Table 10

CAR Minimum Intensity for

Anti-Collision Lights[a]

Angle above or below horizontal plane	Effective Intensity, Candles
0° to 5°	100
5° to 10°	60
10° to 20°	20
20° to 30°	10

[a] Because of the difficulty of obtaining complete azimuthal coverage in some installations, due to obstruction by empennage, obstruction is allowed up to a maximum of .03 steradians of solid angle within a solid angle of 0.15 steradians centered about the longitudinal axis in the rearward direction. However, for aircraft covered by parts 3, 6, and 7 of the regulations, obstruction up to 0.5 steradian in any direction is permitted.

range from 40 candles near 0 degrees (dead ahead) to 5 candles from 20 to 110 degrees. The large difference is based on the fact that closing speeds at or near 180-degree (head-on) approaches are much higher than those at smaller convergence angles. If it is desired that warning times be equal for all probable collision courses, then the visual range of the lights must be proportional to closing speed. To achieve this it is generally necessary to provide much higher intensities forward than at angles more abeam. The extraordinary range of possible aircraft speeds and the variability of atmospheric transmissivity within VFR limits make it impossible to specify a distribution of intensity that precisely accomplishes the objective. Rough calculations on some selected sample cases are instructive.

Table 11 gives relevant data for two aircraft, each traveling at 300 miles per hour, for various angles of convergence, based on a required warning time of 30 seconds and an atmospheric transmissivity of 0.53/mile (the boundary between "clear" and "light haze," equivalent to a reported daylight visibility of about 6 miles). The intensity data are taken from Fig. 4 of Chapter V.

If this table is compared with Table 7, it is evident that:

1. The CAR minimums are much lower than necessary to meet the requirements on which the table is based through all angles of convergence from 180 degrees (head-on) to 60 degrees (aspect angles from 0 to 60 degrees).

2. The abruptness of the reduction in the intensity required by the CAR at 20 degrees aspect angle does not correspond with the much less abrupt changes in intensity near 20 degrees, shown in the table.

3. The range of intensities in the table covers a much wider gamut than the range in the CAR.

But the assumptions on which the table are based are very narrow. Similar tables covering all possible values of the parameters would be encyclopedic. It is useful here to consider qualitatively how changes in the assumptions would change the results.

1. If the atmospheric transmissivity were less than 0.53/mile, for example 0.25/mile, equivalent to a daytime visibility of about 3 miles, all the required intensities would be increase. At the lower convergence angles, the increases would be substantial, for example, from 13 to nearly 100 candles at 40 degrees convergence angle. Near head-on, the increases would be enormous. At 180 degrees

Table 11

Required Signal Intensity for Various Collision Courses

(Speeds of aircraft = 300 miles per hour, transmissivity = 0.53/mi., warning time = 30 seconds)

Convergence angle	Aspect angle	Closing speed, mph	Required sighting range, miles	Required signal intensity, candles (approx.)
180° (head-on)	0° (dead ahead)	600	5	300
140°	20°	560	4.7	200
120°	30°	520	4.3	130
100°	40°	460	3.8	80
80°	50°	385	3.2	35
60°	60°	300	2.5	14
40°	70°	200	1.7	4

the required intensity would jump from 300 to nearly 10,000 candles.

2. If the atmospheric transmissivity were greater than 0.53/mile, the required intensities would be lower, significantly so near head-on. At 0.73/mile, the boundary between "clear" and "very clear," the requirement of 300 candles for the head-on case would be reduced by nearly half.

3. If the assumed speed of 300 miles per hour were increased, substantial increases in intensity would be required, again especially near head-on. If for example the speeds were 50% greater (450 miles per hour) the intensity required for the head-on case would be about ten times greater, or about 3000 candles.

4. If the assumed speeds were reduced, the required intensities would be substantially lower. At speeds of 200 miles per hour, the intensity required dead ahead would be 40 candles.

5. If the speeds of the two aircraft were unequal, then for a given convergence angle the aspect angle for the slower aircraft would be greater, and the aspect angle for the faster aircraft would be less than in the case of equal speeds. Therefore, the variation of required intensity with aspect angle would be greater for the fast aircraft than for the slow one. However, the maximum value, at 0 degrees aspect angle for the head-on collision, would be the same for both aircraft. This does not imply that intensity requirements are similar for fast and slow aircraft; if both aircraft are high speed, then the possible closing speeds (and therefore, the required intensities) include higher values than if only one of the aircraft is high speed, and the corresponding required intensities are much higher.

6. If the assumed warning time of 30 seconds is changed by some ratio, this has the same effect as a change in aircraft speeds in that ratio. Thus increasing the required warning time to 45 seconds has the same effect as increasing speeds from 300 to 450 miles per hour, discussed above. However, there is no single warning time applicable to all collision situations (Applied Psychology Corporation, 1961a). In general, required warning time is greater for higher-speed aircraft, and for larger and less easily maneuverable aircraft, but it is very difficult to specify precisely what warning time is required in any given situation.

7. If the assumed threshold illumination of 0.5 mile-candle underlying the data in the figure from which intensity values were obtained is inapplicable to a given situation,

then the required intensity must be changed proportionately to the applicable threshold. Factors such as background luminance, the presence of other light sources, and pilot alertness can profoundly affect thresholds.

It is evident from all the above that no simple set of intensity requirements, even if substantially increased over present CAR requirements, can provide visual ranges sufficient to insure effective visual collision-avoidance capability in all situations possible under today's traffic conditions. The choices open to the regulatory agency therefore must reduce to one of three general approaches.

1. It must accept a degree of unavoidable risk, understanding that there will be occasions when VFR pilots cannot effectively control the outcome of a possible collision situation.

2. It must so restrict VFR operations as to reduce the incidence of these occasions to a small fraction of the current number.

3. It must accept and operate under VFR rules considerably more complex than present ones, including general increases in intensity of navigation lights, different specified intensities for different classes of aircraft, and new definitions of limiting VFR conditions tailored more to traffic conditions.

These three approaches are not sharply distinguished. Compromises might have elements of all three approaches. Intensity requirements, for example, must necessarily be limited by important considerations, including the possibility of deleterious effects due to backscatter.

In specifying intensity minima it is helpful to consider the difference in requirements for aircraft in different speed classes. Even though they may sometimes be involved in collision courses with faster aircraft, those with low maximum speed or whose operations are restricted to low-speed airlanes do not require intensities as high as aircraft with high cruising speed. On the other hand, the intensities they require must be nearly uniform in all directions, since the slow aircraft may be approached from any direction by a fast aircraft, and its speed and the approach direction do not affect the net closing speed as profoundly as when both aircraft are fast.

The minimum intensity requirements for position lights, shown in Table 12, has been formulated to provide guidelines, not to prescribe a detailed regulation. In view of the

Table 12

Suggested Minimum Intensity Requirements (Candles)

for Aircraft Position Lights

Angle from right or left of longitudinal axis, measured from dead ahead	Low-speed aircraft	High-speed aircraft
0° to 20°	100	500
20° to 40°	75	300
40° to 180°	50	100

uncertainty of much contributory data, the values must be based on somewhat arbitrary determinations. There is little doubt, however, that the minimum intensities listed would be much more appropriate to actual needs than present requirements. Different requirements are given for high-speed and low-speed aircraft. The class cutoff must be somewhat arbitrary. It is suggested that a maximum cruising speed of the order of 200 miles per hour be used, but detailed investigation may suggest a different or even flexible classification.

The present CAR prescribe lower minimum intensities at elevation angles above and below horizontal than in the horizontal plane. This conforms generally with reasonable requirements, since the visual ranges required in the presence of altitude differences (and therefore elevation angle differences) decrease with the difference. There is no evidence that the present CAR requirements for position lights are inadequate in this respect. Since they are defined as a proportion of the intensity in the horizontal plane, an increase in the requirement for the latter is accompanied by a proportional increase at all elevation angles. It is suggested therefore that this part of the present CAR be left intact.

Maximum-intensity requirements in the overlaps should be rewritten, in order to insure reasonable cutoffs. Essentially, what is, or ought to be required, is that the intensity of the unwanted signal from the adjacent sector be sufficiently lower than the desired signal in a given direction that the desired signal dominates and therefore adequately identifies the sector. The present CAR recognizes the engineering difficulty of obtaining an exact boundary and provides no maximum intensity in the first 10 degrees adjacent to a boundary. In the next two adjacent ten-degree zones, specific maximum intensities are given. This makes no allowance for lights of appreciably higher intensities than those prescribed as minimum. It is unreasonably difficult to meet the same cutoff requirements in both high- and low-intensity lights when the cutoff maximums are given in definite values of intensity. This difficulty, recognized in one instance, resulted in Paragraph 4b. 634-1 of CAR 4b, which specifies the cutoff maximums for the forward overlap zones with high-intensity lights as percentages of the forward peak intensities. While this is an improvement, the intent of the cutoff requirement would be served best if (a) all cutoff requirements were given as percentages and (b) the requirements were given as percentages of the <u>dominant</u> signal intensity in any given direction.

This would insure adequate cutoffs in terms of what an observer would see in a given direction, and would provide equally effective cutoffs with lights of any intensity.

Accordingly, it is suggested that the maximum overlap intensity requirements be changed as indicated in Table 13.

It is generally desirable to provide sharp cutoffs at sector boundaries. The somewhat loose requirements given in Table 13, and in the present CAR, reflect the need to compromise this requirement with engineering feasibility. If developments in the state-of-the-art permit, manufacturers should sharpen the boundaries as much as is practicable, and revision of the regulations should be considered to call for more precise boundaries.

A particular problem arises with the quadrantal sector-coded system discussed earlier. Here the rear overlap introduces a more pervasive ambiguity than do other overlaps. Since there has been no engineering experience with this problem, it is inappropriate at this time to require sharper overlaps at this boundary. However, as equipment is developed to provide quadrantal coverage, the objective of requiring an especially sharp boundary to the rear should be kept in mind.

Anti-collision light intensity requirements. Anti-collision lights are omnidirectional, and their intensity at any angle of elevation is uniform in all azimuthal directions. Therefore the CAR requirement is stated in terms of the minimum intensity required at various elevation angles. The possibility (and desirability) of using lights of appreciably higher intensities than the required minimums suggest that the requirement be stated in two ways, a minimum intensity in and near the horizontal plane, and, for other elevation angles, proportions of actual intensity in the near-horizontal zone.

It might be argued that there is no harm in designing a light with a very intense but very narrow horizontal beam, provided it is above some minimum at other elevation angles. However, this would not constitute good design; by the very narrowness of the intense part of the beam, its usefulness would be more limited than the numerically high value of peak intensity would suggest. The beam shape contemplated by the over-all requirements should be the goal of designers. In designing higher-intensity equipment there is no particular difficulty involved in preserving beam shape, and every reason to insure good design by doing so.

As in the case of position lights, the proposed higher intensities shown in Table 14 are given in classifications

Table 13

Suggested Maximum Intensity Requirements

for Position Light Overlaps

Overlap zone	Maximum intensity[a]
10° to 20° from sector boundary	.10 I
More than 20° from sector boundary	.025 I

[a] "I" is the actual intensity of the required signal in any specified direction.

Table 14

Suggested Minimum Effective Intensities for

Anti-Collision Lights

Angle above or below horizontal plane[a]	Minimum intensity	
	Low-speed aircraft	High-speed aircraft
0° to 5°	500 candles	2000 candles
5° to 10°	.60 I[b]	
10° to 20°	.20 I	
20° to 40°	.10 I	

[a] If complete coverage is obtained with two anti-collision lights, each intended to cover one hemisphere, the upper or lower, then the indicated directions shall refer only to the covered hemisphere.

[b] I is the lowest measured intensity in the 0° to 5° zone of the anti-collision light under examination.

for high-speed and for low-speed aircraft. The general discussion of the reasoning behind the classification for position lights applies here. The intensity requirements, since these are flashing lights, are in terms of "effective intensity," computed from photometric data, as called for in the present CAR. In addition to increased intensity, it will be noted by comparison with Table 10, that an increase in elevation angle coverage from 30° to 40° is called for. This is to insure that the anti-collision lights of banking aircraft will remain reasonably visible.

Because of the difficulty of avoiding obscuration by aircraft structures, some incompleteness of coverage is permitted under the present CAR. It is almost always possible to solve this problem, but it is often at the cost of additional light fixtures or troublesome installations. Aircraft covered by Part 4b of the CAR are permitted no more than 0.03 steradian of obstruction, which must be confined to 0.15 steradian centered about the longitudinal axis rearwards (a cone with a half-angle of about 12½°). Since this obstruction is confined to the rear where possible closing speeds are at a minimum, it may be argued that the loss of the high-intensity flashing anti-collision light and the consequent dependence on the much lower intensity steady-burning rear position light does not seriously reduce safety. This argument cannot be used for aircraft covered by other parts of the CAR, for which a much larger obstruction is allowed (0.5 steradian) without restriction of direction. To allow any obstructions at all seems questionable, even if they are restricted to rearward. Statistics indicate that this approach direction accounts for a high proportion of collisions (Fisher & Howell, 1957), even though analysis suggests it ought to be the safest direction--an anomaly perhaps explained by the fact that many collisions occur in more or less unidirectional traffic near airports. It may also be connected with the fact that pilots are generally "blind" to the rear so that in an overtaking collision the entire responsibility for avoidance rests on one pilot. Finally, if an overtaking collision also involves climbing or descending courses, both pilots may be "blind" (Fisher & Howell, 1947; Calvert, 1958).

Under these circumstances, greater intensity than normally necessary for detection may be needed to attract the pilot's attention. It is difficult to assess the effect of seemingly small exceptions to requirements, but deviations constitute some increase in risk and should be allowed only after a determined effort to obviate their apparent necessity.

Power required for increased intensity. Increased intensity can be obtained generally only at the expense of increased power consumption. Since the suggested minimum

intensities for navigation lights are substantially higher than present CAR minimums, the power requirements will be correspondingly higher. On large or high-powered aircraft, these power demands may not seem excessive. On smaller or even medium-powered aircraft, considerations of power availability may be decisive in determining the feasibility of the recommendations, or the extent to which they may have to be compromised.

Since the proposed requirements differ from the present CAR requirements not only in regard to generally higher intensity, but also in distribution of intensity, and possibly in color, so far as the taillight is concerned, estimates of power cannot be based on a simple ratio. In estimating the new power demands, the characteristics of a variety of conventional and newly developed navigation lights have been examined, and the present state-of-the-art in illuminating engineering has been considered. The estimates are nevertheless only rough approximations. When actual equipment to meet requirements is designed, it may be found possible to improve on these estimates, or if necessary, in difficult cases, to accept lower efficiency and therefore, higher power consumption.

Table 15 lists the power consumption of present typical navigation light equipment and estimates of the power consumption required to produce the suggested higher intensities listed in Tables 12 and 14.

Traffic Rules, Rules-of-the-Road, and Minimum VFR Conditions

It has been shown that avoiding collisions visually is difficult and sometimes impossible when (a) closing speeds are high, (b) flight visibility is marginal, and (c) approaches occur from directions in which cockpit visibility is restricted.

As the number of aircraft and their cruising speeds increase, these difficulties increase, and pilots are less able to detect intruder aircraft in time to analyze collision probabilities and to take effective action when indicated.

Suggested improvements in light systems would help reduce the number of uncertain or impossible collision situations. Other steps can be taken by regulatory action or by operational procedures to improve the situation further.

From the viewpoint of visual collision avoidance alone, a number of seemingly straightforward steps are suggested. When these are viewed in the context of the entire scope of flight operations, they become more complex.

Table 15

Power Consumption of Navigation Light Systems Meeting Present CAR Requirements Compared with Estimated Power Consumption of Systems Meeting Proposed Higher Intensity Requirements

Light	Power Consumption of Present Equipment, Watts	Estimated Power Consumption to Meet Proposed Requirement, Watts	
		Low-Speed Aircraft	High-Speed Aircraft
Wing (2 required)	50-80	200	750
Tail (1 required)	15-30	200	750
Anti-collision (2 normally required)	175-220	300	1200
Complete system	235-320	700	2700

For example, there are many hazards in the air beside collisions. There would be little point to reducing one danger if in the process the danger from other hazards was increased even more. Economic considerations cannot be ignored. Competing demands for pilot attention and for air traffic facilities complicate the problem of reconciling different requirements, especially when regulatory action is involved. The proposals herein have been geared to practical considerations and to reasonable (if heavy) demands on engineering capability. The suggestions in this section may not lead to regulatory action at all or may be only partially incorporated into regulations. Furthermore, the proposals are presented in general form, since the detailed content of regulations or procedures is in some cases subject to more investigation or analysis.

The proposals may be grouped in the following categories: (a) restricting possible collision courses, (b) raising VFR minimums, (c) increasing cockpit visibility, and (d) changing rules-of-the-road.

Restricting possible collision courses. Paragraph 60.32 of the CAR, Part 60, Air Traffic Rules, restricts directions in VFR level cruising flight 3000 feet or more above the surface as shown in Table 16.

These restrictions reduce the possible incidence of near head-on collision situations, especially in the denser east-west directions. To the extent that they are effective, they reduce the number of high-closing-speed situations shown to be difficult or impossible to cope with.

According to the rule, opposing traffic along an east-west airway should be at different altitudes. But other traffic crossing the airway, or airway traffic changing altitude or for some reason failing to hold to specified altitude, and traffic outside airways, may be involved in converging courses at any angle. The incidence of near head-on approaches is very much reduced by the rules, but not eliminated.

Every effort should be made to set up rules to insure against head-on approaches. Quadrantal altitude separation would be much more effective than the two-sector separation of the present rules, but would be complicated, requiring either a large altitude change to get to the next altitude with the same direction, or, alternately, too close an altitude segmentation for operational safety.

The use of one-way climbing and descending corridors is also helpful, as are the general corridor restrictions near airports. In general, pilots of high-speed aircraft

Table 16

VFR Crusing Altitudes

Magnetic Course	Altitude	
	Below 29,000 feet	Above 29,000 feet
0° to 179°	odd thousands plus 500 feet	4000-foot intervals beginning at 30,000 feet
180° to 359°	even thousands plus 500 feet	4000-foot intervals beginning at 32,000 feet

will find it difficult or impossible to avoid colliding with other aircraft in head-on approaches; even with moderate-speed aircraft the time for decision is short and the correct decision difficult to determine.

Raising VFR minimums. In general, VFR minimums should be raised, regarding both flight visibility and separation from clouds. The present regulations (Part 60, paragraph 60.30) set up three different minimum flight visibilities, 1, 3, and 5 miles, for four categories of air space. In the continental control area, the 5-mile requirement recognizes that speed ranges are high at high altitudes, thus requiring higher visibility for effective VFR. Even so, with the intensities required by the CAR, signal visibility in marginal conditions is inadequate at the speeds commonly encountered.

If intensities can be increased along the lines recommended, and head-on approaches eliminated, the presently required minimum visibility may be satisfactory. Nevertheless, it is suggested that the minimum be raised to 6 miles, partly to provide a safer limit, and partly because this would restrict VFR to atmospheres designated by the International Visibility Code as "clear" or better. If head-on approaches cannot be ruled out, then visual avoidance for very high-speed aircraft must be considered unlikely under marginal conditions and very difficult at best.

A note in the CAR (paragraph 60.30) indicates that VFR minimums are to be treated conservatively. This advice cannot be overemphasized. As indicated repeatedly, when any factor is marginal--flight visibility, cockpit visibility, pilot attentiveness, convergence angle, speed, etc.--the pilot's task is difficult. When several factors are marginal, the difficulty may be enormous. In all areas where the pilot has a choice he should be very cautious.

For this reason the 3-mile minimum flight visibility requirement for control zones, control areas, and transition areas is too low. These areas may contain both high-speed and low-speed aircraft. Furthermore, many aircraft are not (and may not be, for a long time) equipped with lights of high intensity by current standards. Traffic densities are higher, and demands on pilot attention more severe. It is also likely to be more difficult to insure against head-on approaches.

For all these reasons, therefore, it is felt that the 3-mile visibility minimum should, as suggested for the continental control area, be raised to 6 miles, "clear" or better. This change is especially important with present light intensities, but is recommended even if intensities can be substantially increased.

The requirement of 1-mile visibility outside controlled airspace is far too low for avoiding collision unless the possible conditions under which collision can occur are severely restricted. One-mile visibility is a "thin fog" condition. A signal of 100 candles has a range of about 1-1/4 miles, and a 1000-candle signal about 1-3/4 miles--adequate for relatively controlled low-speed flight near airports, but not suitable for general flying. This requirement should be raised or should be narrowly restricted to situations where such low visibility can be considered adequate.

The requirements for cloud clearances are not sufficiently conservative. Cloud distances are often difficult to estimate. They should be sufficient for an aircraft near them to evade an aircraft emerging from them. The requirement should be reexamined in terms of the accuracy with which separation from clouds can be maintained and the collision problems presented by emerging aircraft.

The CAR's definition of flight visibility is vague, particularly the part covering nighttime visibility: "the average forward horizontal distance, from the cockpit of an aircraft in flight, at which prominent lighted objects may be seen and identified at night." The definition of night visibility should not refer to "prominent objects," which are irrelevant, but to lights of specified intensity as seen against specified backgrounds. Although it is evident that the definition is inadequate, satisfactory definitions are difficult to establish. The question of a suitable definition related to actual determinations of visibility should be investigated.

Increasing cockpit visibility. Increased cockpit visibility is an evident and long-recognized requirement for achieving effective visual collision avoidance. Generally, a pilot must be concerned with intruder threats from all directions, yet windows on most contemporary aircraft provide very limited visibility.

Mirrors, periscopes, and similar scanning devices can partially overcome visibility restrictions, but they are inferior to direct line-of-sight viewing and are therefore poor substitutes for increased window space. Pilots can also increase directional coverage by maneuvering, but this is hardly a useful general technique.

Although no pilot should assume that any approach direction is safe, the degree of danger in different directions varies with different aircraft. Slow aircraft are subjected to nearly uniform danger in all azimuthal directions. They should therefore be required to have

much larger window areas than fast aircraft. Fortunately this conforms with current practice.

A serious visibility deficiency of modern aircraft is in sight lines above and below. Most double-blind approaches involve such sight lines. Every effort should be made to require and obtain large increases in upward and downward visibility.

No conceivable increases in cockpit window areas can be expected to provide full visibility. It is important therefore to develop optical devices to supplement direct visual coverage. Since they provide coverage in otherwise blind directions, their limitations may be tolerable. They are likely to be particularly valuable to a pilot in determining before he maneuvers that airspace is clear. When such devices are fully developed and their capability proved, regulations requiring them and governing their use should be considered.

Changing rules-of-the-road. Paragraph 60.14 of the CAR contains rules governing maneuvers for avoiding collision and specifying rights-of-way in potential collision situations. Many of these rules are concerned with giving precedence to aircraft in distress or to less maneuverable aircraft. Others, however, modeled after marine rules, give the "right-of-way" to one of two involved aircraft depending only on relative sight-line bearing. A note suggests that no pilot is ever relieved of responsibility for avoiding collision. However, it is recommended that all potential collision courses require complementary avoidance by both pilots. It may often happen that one pilot will not see the other, so that the burden of avoidance will fall by default on only one pilot. But if both see each other, the short time available in many situations requires that both maneuver. Furthermore, the pilot who does not have the right-of-way may fail to detect the other, or he may evaluate the danger of collision incorrectly. In any event, prudence requires that any pilot who determines that a collision risk exists take measures to avoid colliding.

Designing rules-of-the-road to satisfy this requirement is not easy; any set of rules is likely to involve incorrect maneuvers when an inevitable degree of uncertainty exists, especially when the closing speed is high. Pilots should try to evaluate collision risk carefully before engaging in an avoidance maneuver but should not delay such a maneuver once the risk has been judged to exist. In general, premature maneuvers will not reduce the risk of collision, to the pilot's knowledge; late maneuvers will not provide sufficient time to escape the zone of possible collision.

The present rules do not require or suggest the possibility of avoiding collision by climbing or descending. Such maneuvers are occasionally used and systems of combined turning and altitude-changing maneuvers have been devised. Such maneuvers are more troublesome for pilots; in the absence of better altitude-difference information than is generally available, these maneuvers may be of doubtful value for systematic use. However, they are useful for last-moment acts of desperation. But if altitude-coded light systems come into use and provide adequate altitude information in collision situations, then altitude evasion might be the preferred maneuver.

Under present conditions, altitude avoidance maneuvers might be considered for rule-making if it can be shown that they are generally effective and would be more so if rules could be designed that would assure complementary maneuvers.

Double-blind overtaking, with one or both aircraft changing altitude, is one of the most dangerous collision approaches; it has been the cause of a high proportion of collisions. Improved cockpit visibility would greatly reduce this danger.

Rear-view mirrors and optical aids are only a partial answer, and in any event, are not now available or adequately developed.

A change in the rules may be of some help in reducing the danger of double-blind approaches. Pilots are required to watch for collision possibilities in all directions. Nevertheless it would be helpful to spell out that the pilot of any aircraft about to engage in a climbing or descending maneuver is responsible for making sure that the air is clear of collision threats from normally blind directions, even though he believes the present overtaking rules give him the right of way.

In effect such a rule says that a pilot flying level has the right of way over a pilot changing altitude. This may sound superfluous or self-evident, but the special danger of double-blind vertical collisions suggest that the emphasis of a specific rule might be helpful.

Phase III. Long-Range Program to Develop New and Improved Navigation Light Systems

The suggestions in this phase constitute a comprehensive program to investigate methods of improving navigation light systems and of increasing their usefulness. Some of

the suggestions call for radically new concepts, such as altitude coding. Others are directed toward establishing details of design to insure maximum effectiveness for a given concept. Finally some parts of the program are intended to improve visual avoidance techniques, and to ascertain their precise limits of usefulness.

One of the most important techniques available to a pilot is the use of the fixity-of-bearing criterion. It was pointed out that a key factor in the success of the technique is the precision with which a pilot can determine bearing fixity. In order to be able to assess the usefulness of the criterion, it is essential to carry out experiments which will provide valid estimates of the threshold of bearing fixity detection in operational situations. The thresholds must be determined for steady and flashing lights, and for other possible parameters such as intensity or color. Leibowitz (1955) found that movement discrimination is aided by reference lines in the field of view. This suggests the possibility of providing a fine grid in window areas, and this should be investigated.

The effect of backscatter on target visibility has been found to be unrelated to differences in the backscattering light (Applied Psychology Corporation, 1962a). Subjective evaluation of backscatter suggests striking differences nevertheless. It is thus strongly suggested that the possible psychological effects such as distraction, disturbance, or disorientation, be investigated. The results will be important in deciding such questions as the choice between red and white for the color of anti-collision lights and between different flashing modes.

The conspicuity of aircraft lights against backgrounds of city lights has been investigated in a static situation (Applied Psychology Corporation, 1962e). Further investigation, with relative movement characterizing most operational situations, should be undertaken.

Various light coding techniques were discussed in Chapter III. A broad study should be undertaken to determine, under comparable operational conditions, the relative efficacy of these techniques, in terms of speed and accuracy of interpretations, and suitability for conveying different amounts of information.

It has been found that pilots can be trained to improve their ability to estimate distance and relative altitude of intruder aircraft (Applied Psychology Corporation, 1962c). In view of the importance of this information in visual collision avoidance, a broader investigation should be undertaken to determine what the limits of estimating capability are in general operation.

The use of lights to improve daytime conspicuity has been suggested frequently. It was shown in Chapter VI that there is little likelihood of providing effective daytime lighting for the full range of daytime requirements. The gravity of the daytime problem suggests that a systematic investigation should be undertaken to determine precisely what can be done with lights.

The most promising development in the information content of light systems is the possibility of coding altitude information into navigation lights. This has been discussed in detail in Technical Report No. 1 (1961a) and summarized in Chapter II of this report. Two tests have been made. One, in NAFEC's F-100 simulator, suggested an advantage with altitude coding in pilots' ability to determine altitude, and a substantial advantage in determining courses involving change of altitude (Applied Psychology Corporation, 1962b). The results of the second test, a flight test, showed a marked improvement on both counts with altitude coding (Applied Psychology Corporation, 1962f). These preliminary results support the desirability of a systematic investigation. A number of questions require answering:

1. What altitude segmentation would be optimum?

2. What cycle length would be optimum?

3. How shall coding be achieved?

4. What rules-of-the-road would most effectively use the information?

5. Under what conditions is altitude coding useful? (high altitudes? near airports? etc.)

6. What are the engineering problems of deriving an altimeter signal and converting it into light signals?

7. What inaccuracies, confusions, errors, etc., will be encountered and what will their effect on operations be?

8. What special problems will arise if altitude coding is to be standardized under the CAR?

Other kinds of information that may be useful if coded into navigation light systems are (a) maneuver, (b) speed, and (c) angle of elevation.

Of these, maneuver appears of greatest interest, particularly change of altitude (which may be of particular interest if altitude coding should be rejected as infeasible)

and turn indication, of interest in the use of the fixity-of-bearing criterion. In using the criterion, both aircraft must be on straight, constant-speed courses. A pilot knows whether his own course meets the requirements but generally does not know about the intruder. Turn-maneuver indication would help him determine this.

The indication may be rudimentary, showing only that some maneuver is under way without specifying what it is; or it may show which of the four basic maneuvers (or two, in a simplified version) is in process. Detailed maneuver information would enable a pilot to know that correct complementary avoidance maneuvers have been undertaken by both aircraft. (It should be noted that one of the 19 navigation light systems on display at NAFEC includes such a 4-element maneuver indication.) A research program should investigate questions of feasibility, usefulness, detailed requirements, etc., of the various possible types of maneuver coding.

Speed coding appears to have some usefulness, but it is felt to be less promising than either altitude or maneuver coding. At the present time it is considered unlikely that any additional complexity in navigation light systems is justified for this purpose, particularly if altitude or maneuver information (or both) is added to sector coding.

Elevation angle coding, similarly, appears much less useful than altitude coding and does not justify the added complexity.

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